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AFRPL-TR-81-105

PULSED PLASMA THRUSTER IGNITION STUDY

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Final Report for the period May 1980 through September 1981

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AIR FORCE ROCKET PROPULSION LABORATORY
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A study of ignitor plug operation in a one-millipound pulsed plasma thruster
has been performed. Inductive, rather than resistive coupling of the
ignitor plug cathode to the thruster cathode electrode has been shown to
significantly reduce a carbonaceous deposit buildup on the plug face. A
reduction in plug deposition was also demonstrated by the use of a high
current, short pulse length, plug trigger circuit.

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TABLE OF CONTENTS

2

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

The one-millipound pulsed plasma thruster (PPT) has been developed as a viable alternative to hydrazine thrusters for large satellite station keeping and drag make up functions. Figure 1 illustrates schematically the basic components of the pulsed plasma thruster discharge chamber. As indicated, the ignitor plug semiconductor element arcs over upon the application of a fast rise time voltage pulse from the plug trigger circuit to the coaxial plug anode and cathode electrodes. The plasma puff produced from this semiconductor arc breakdown initiates, in turn, an intense plasma discharge between the thruster cathode and anode electrodes. This plasma discharge is sustained by the depolymerization and ionization of teflon fuel bars (not shown in Fig. 1) until the energy stored in the thrusters capacitor bank has been consumed. Electromagnetic body forces within the discharging arc accelerate the dense teflon plasma along the rail type cathode and anode electrodes. The accelerated plasma pulse is ejected from the thruster with exhaust velocities which can be as high as 50,000 m/sec. Typically, the PPT arc discharge pulse length is approximately 30μsecs. Increasing the total energy per thruster pulse and/or the pulse repetition rate results in a corresponding increase in the time averaged thrust. Presently, the one-millipound PPT has an efficiency (less power processor) of 35%, a specific impulse of 2000 sec. and a nominal equivalent steady state thrust of 4.45 mN (1.0 mlb) at a pulse repetition rate of 0.2Hz. The desired thruster lifetime is 1.4×10^7 pulses with a total impulse of 312,000 N-sec (70,000 lb-sec). At present, the demonstrated thruster lifetime is only 2×10^6 pulses. The PPT ignitor plug has been identified as a

6

IGNITOR PLUG
TRIGGER PULSE

COUPLING
ELEMENT

IGNITOR PLUG
(DETAIL A)

DISCHARGE
CAPACITOR BANK
260 μF, 2.4 KV

THRUSTER CATHODE

DISCHARGE
CURRENT ROGOWSKI COIL

THRUSTER ANODE

DETAIL A

IGNITOR PLUG ANODE

INSULATOR

IGNITOR PLUG CATHODE

ANNULAR SEMICONDUCTOR
BREAKS DOWN TO PRODUCE
PLASMA PUFF
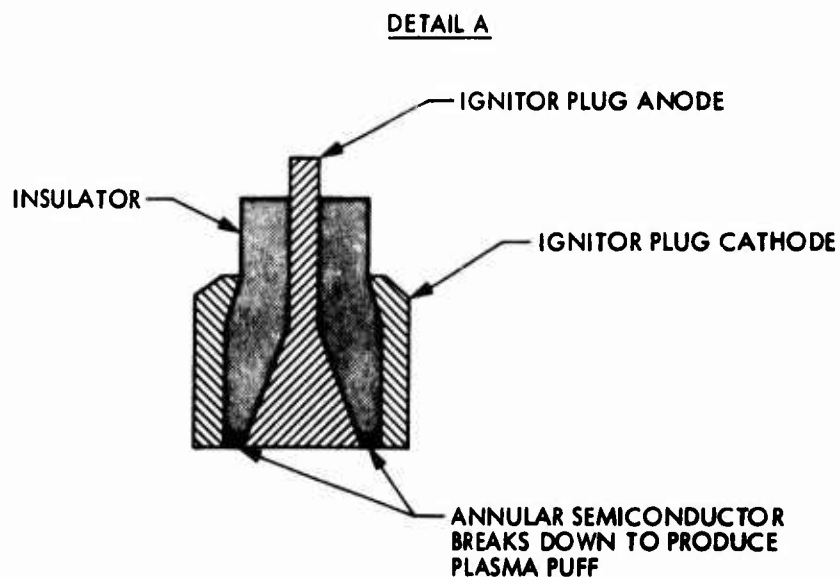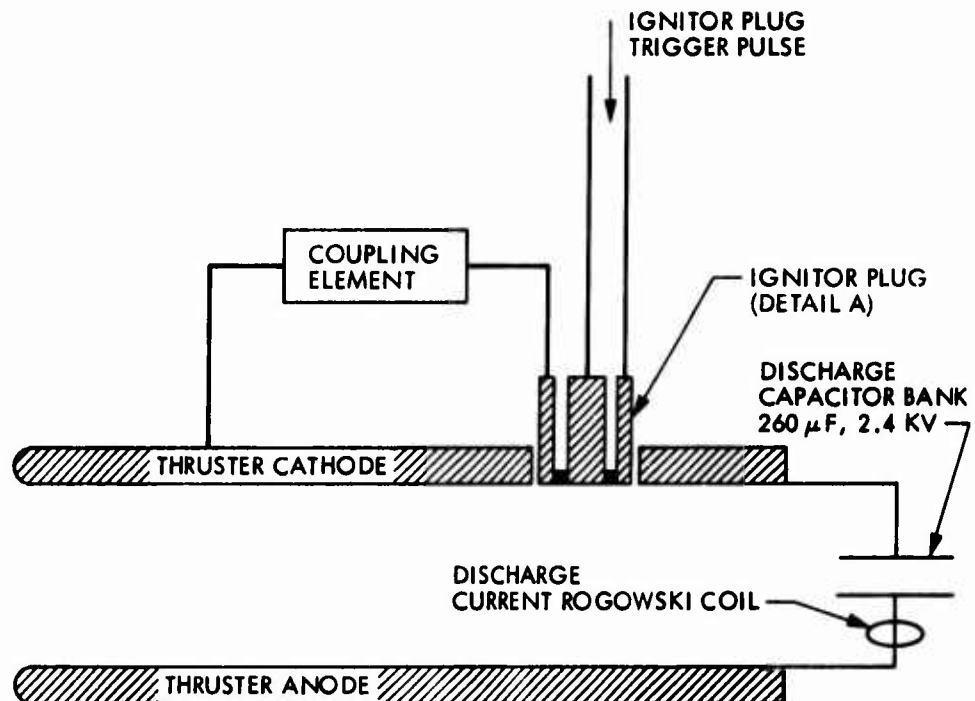
Figure 1.   One-millipound pulsed plasma thruster discharge
chamber component locations.

7

major life limiting thruster component.[1]

Although ignitor plugs have been used successfully in several flight qualified and flight tested micropound pulsed plasma thrusters, their use in the one-millipound pulsed plasma thruster has not met with the same degree of success. Early tests at the Fairchild Republic Corporation (FRC) showed that the ignitor plug cathode underwent severe erosion when the plug was press fitted into the thruster cathode with the plug cathode and thruster cathode electrically connected directly, as in the case of micropound thruster designs. An apparent remedy for this problem was to isolate the ignitor plug from the main cathode by a 0.76 mm vacuum gap and use a 1.0 ohm resistor to electrically connect the plug cathode and thruster cathode. However, this approach resulted in large amounts of carbonaceous deposits accumulating on the plug face. Eventually these carbonaceous deposits would become sufficiently thick and conducting to effectively short circuit the ignitor plug semiconductor element and prevent plug firing with the subsequent cessation of thruster operation. To overcome this deposition problem, a different trigger circuit design was implemented. This new trigger circuit produced a low voltage, high current pulse which continued to fire the plug reliably with large deposits accumulated on the plug face. Using this redesigned trigger circuit, Palumbo and Begun were able to continue a thruster life test until approximately 2×10^6 thruster pulses were obtained on a one-millipound pulsed plasma thruster before voluntary shutdown.[2]

The results of the Fairchild Republic Corporation one-millipound PPT

8

life tests illustrated the sensitivity of the link between ignitor plug erosion, deposition and thruster lifetime. In order to better understand ignitor plug erosion and the arc initiation processes in a one-millipound pulsed plasma thruster, a study was initiated at the Jet Propulsion Laboratory (JPL) to examine these phemonena. The pulsed plasma thruster ignition system study at JPL was conducted under the sponsorship of the Air Force Rocket Propulsion Laboratory (AFRPL). The specific objectives of this study were (i) to determine the coupling required between the one-millipound PPT ignitor plug cathode and the main discharge cathode to give the best thruster system life time and; (ii) to develop a basic understanding of the PPT ignition process in order to provide guidelines for ignition subsystem improvements.

The JPL ignition system study was divided into five tasks:

(i) Arc Cleaning Experiments - Included here were assembly of a vacuum system and instrumentation test installation sufficient for one-millipound PPT operation, development of a baseline ignitor plug erosion/deposition monitoring technique, and the determination of ignitor plug erosion/deposition behavior for different ignitor plug resistive coupling elements to the main thruster cathode electrode.

(ii) Optimum Coupling Determination - This task involved the parametric investigation of the effect on ignitor plug erosion/deposition caused by non-resistive coupling elements, the effect of ignitor plug trigger pulse characteristics on plug erosion and operation, and the determination of the erosion mechanisms occurring on the ignitor plug face.

(iii) Ignitor System Analysis - This effort was directed towards determining the ignitor plug discharge energy, the plug discharge shot-to-shot repeatability, the physical extent and velocity of the ignitor plug

9

plasma plume and conducting a preliminary spectroscopic study of the ignitor plug and pulsed plasma thruster arc discharge.

(iv) Ignition System and Discharge Chamber Interaction Analysis - This task dealt with the implementation of appropriate diagnostic techniques on the PPT discharge chamber, ignitor plug and coupling element to ascertain the interactions occurring between these thruster components and the effect of these interactions on overall thruster performance.

(v) Extended Life Test - An extended thruster/plug life test was performed to verify the results and predictions of the preceeding tasks.

Some of the results of the JPL ignition system study have already been reported in the open literature.[3,4] It is the purpose of this final report to present a detailed account of the work performed during the entire program period. This report is divided into sections dealing with each of the aforementioned tasks.

2.0 ARC CLEANING EXPERIMENTS

Following preliminary indications of different ignitor plug operation with a one and a nine ohm coupling resistor[2], the hypothesis was formulated that the carbonaceous deposit accumulation on the ignitor plug face might be affected by the magnitude of the coupling resistance. The objective of the arc cleaning experiment was to vary ignitor plug coupling resistance over a wide range and determine that coupling resistance value, if any, which minimized the accumulation of carbonaceous deposit on the ignitor plug face.

2.1 Apparatus and Procedure

Thruster:

A one-millipound pulsed plasma thruster was supplied by the Air Force Rocket Propulsion Laboratory for the duration of the test program. The particular thruster provided was a laboratory model developed by the Fairchild Republic Corporation for a variety of test programs and has been described in detail elsewhere.[5] For the ignition study, the thruster was reconfigured as much as was practically possible in a manner similar to the one-millipound thruster currently under development at the Fairchild Republic Corporation. The thruster was fitted with long discharge electrodes developed by FRC.[6] Also, the ignitor plug was flush mounted in the thruster discharge chamber cathode electrode with a 0.76 mm vacuum gap separating the plug cathode and discharge cathode in accordance with recent FRC test results.[2] The ignitor plug trigger circuit developed by FRC[2], utilizing a 1½:1 step down 400 volt

11

output high current impulse transformer, was also used on the thruster. Normal thruster operation was at a pulse repetition rate of 0.2Hz and a thruster capacitor voltage of 2.4 kV. The total capacitance of the thrusters four capacitors was $260\mu F$ resulting in a stored energy per thruster pulse of 750 joule.

Ignitor Plug Housing:

Since frequent ignitor plug removal and reinstallation in the thruster cathode electrode was anticipated throughout the test program, an ignitor plug holder was fabricated to permit easy plug access. This holder was constructed from Mykroy and Phenolic insulating material and by releasing one screw would disassemble for plug removal. Figure 2 compares this plug holder with the plug housing in use on one-millipound pulsed plasma thrusters prior to the flush mounted plug configuration. It should be mentioned that the trigger circuit leads in Fig. 2 were soldered to the ignitor plug cathode and anode electrodes. It was felt that only by soldering these leads could good electrical continuity be assured.

Vacuum Facility and Power Supplies:

All thruster testing was done in a 1.8 x 3.0 m vacuum chamber pumped by a single 0.5 m oil diffusion pump. Average background tank pressure, between firings, was 2×10^{-5} Torr during normal thruster operation. This vacuum tank had a LN_2 cooled liner to reduce plume scattering and to serve a cryopumping function. In addition, the thruster was posi-

12
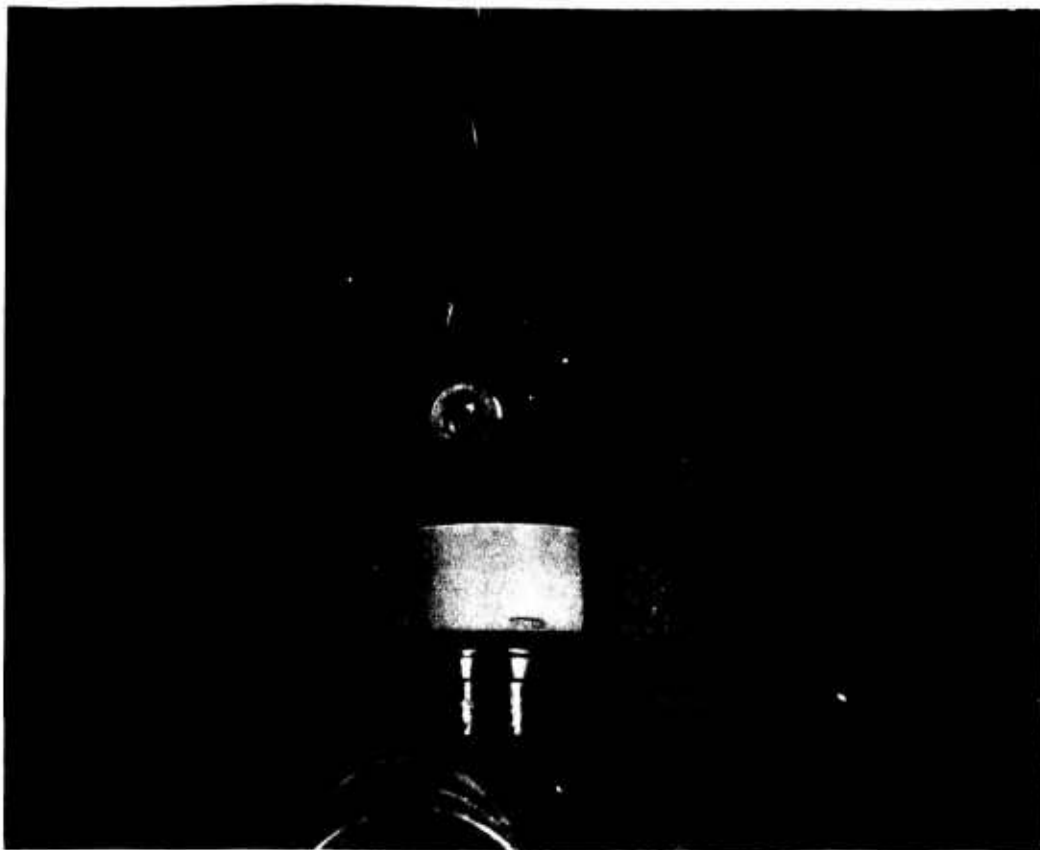
Figure 2.   Comparison of old type potted plug housing (right) and
detachable plug housing (left).

13

tioned immediately above a large LN_2 cooled plate to facilitate thruster temperature control. The PPT capacitor charging supply was a Universal Voltronics Corporation voltage regulated 2.5kV, 3 amp unit which charged the thruster capacitors through a 5K ohm, 1000 watt resistor with a 1.3 sec charging time constant. Stable thruster operating temperatures were maintained by a resistance heating network dispersed around the inside of the thruster body enclosure. Normal thruster operating temperatures varied from about 16-20°C near the ignitor plug housing to about 28-32°C on the energy storage capacitors. Thruster temperatures were monitored at a total of six locations throughout the thruster and were sampled and recorded on a periodic basis by a multichannel temperature recorder. Standard laboratory power supplies provided power for the thruster ignition circuit while a counter box which produced a preshaped trigger signal was built to trigger the ignition circuit and record the triggering events. This counter box also recorded each thruster pulse by using the signal from the discharge current Rogowski coil shown in Fig. 1.

The vacuum tank and associated pulsed plasma thruster power supplies were capable of maintaining normal thruster operation, barring any unforeseen facility breakdowns, in an unattended mode. Figure 3 shows the vacuum facility, power supplies and test equipment used during the PPT ignition study. Figure 4 shows the location of the thruster in the vacuum tank which was such that the exhaust plume was ejected in the vertical direction. This orientation was selected to permit spectro-scopic examination of the thruster arc discharge. The results of these tests are presented in a later section of this report.

14

Figure 3. Vacuum facility and power supplies.
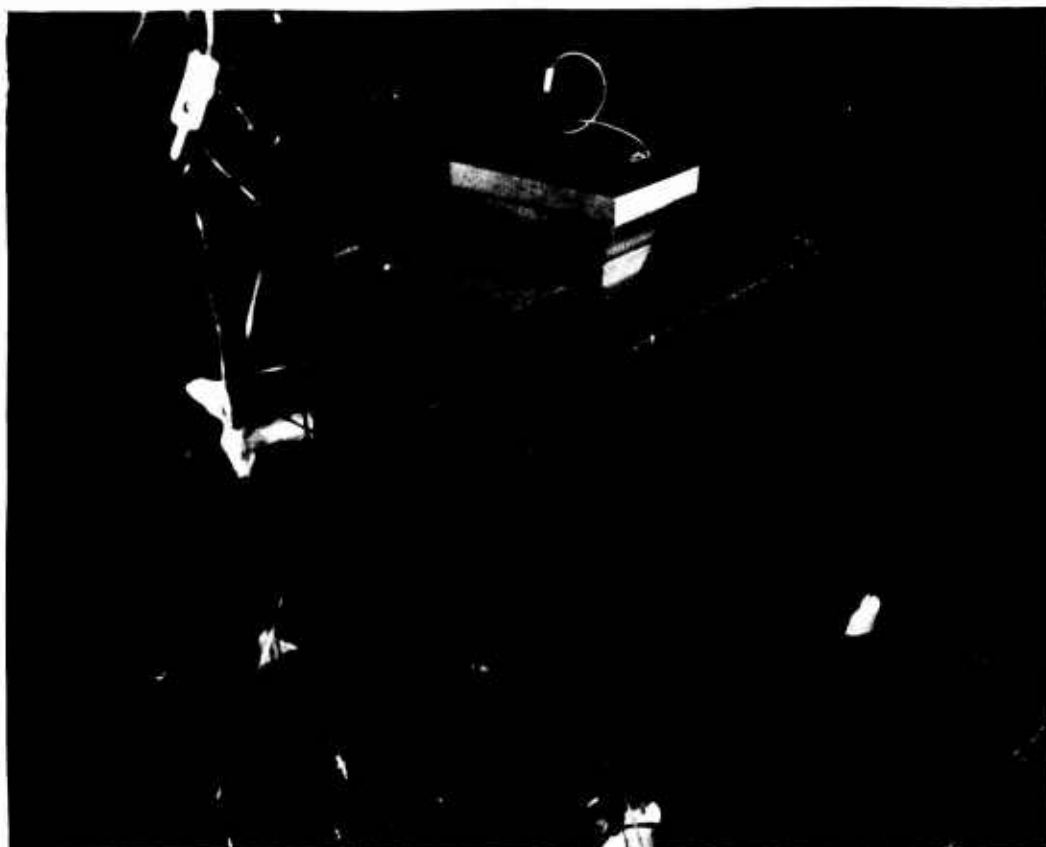
Figure 4. Thruster location in vacuum tank; top cover and
ignitor plug have been removed.

16

Thruster Start Up Procedure:

At the start of each test sequence a standard vacuum facility pump down and thruster start up procedure was followed. After initial rough down, the diffusion pump was turned on and pump down continued until the tank pressure was in the middle to low 10^{-5} Torr range. At this point, LN_2 cooling of the tank shroud and thruster mounting plate was initiated. Tank cool down was fairly rapid so that cryo-pumping by the tank shroud began to take effect after about an hour. The vacuum system was then allowed to pump for an additional twenty four hour period before thruster start up was attempted. At this time, the tank pressure in the vicinity of the thruster was usually about 5×10^{-6} Torr. Thruster start up was initiated at a pulse repetition rate of 0.05Hz, which was the slowest rate of the trigger circuit pulse supply. Due to the large vacuum tank pressure pulses observed during thruster start up, initial operation at 0.2Hz almost always produced thruster prefiring. This was presumably due to a Paschen breakdown occurring across the thruster electrodes during the thruster capacitor bank charge up period. It was usually necessary to gradually increase the thruster pulse repetition rate from 0.05Hz to 0.2Hz over a twenty four hour period. During normal thruster operation the cold cathode vacuum guage indicated tank pressure fluctuations from 7×10^{-6} Torr to 2×10^{-5} Torr.

Thruster Diagnostics:

Rogowski current pick up coils were chosen as the basic diagnostic element to measure thruster operating characteristics. Three separate

17

Rogowski coils were installed at various locations on the pulsed plasma thruster. One coil was located around the center terminal of one of the four energy storage capacitors to record the time evolution of the discharge current pulse. Another coil was located around the coupling element between the ignitor plug cathode and the discharge chamber cathode and recorded the current exchanged between these two cathodes throughout the thruster discharge. The third coil was placed around the lead going to the ignitor plug cathode from the plug trigger circuit and permitted determination of the current actually required to fire the plug from pulse to pulse. Figure 5 shows the locations of these coils.

Both the coupling element and trigger current Rogowski coils were made from 30 guage multi-strand Kapton covered wire tightly wound around coil forms made from two fibrous washers cemented together. The Rogowski coils were calibrated using a capacitor discharge circuit and a 0.00255 ohm series coaxial current shunt. The discharge capacitor Rogowski coil was supplied with the thruster. During calibration of all the Rogowski coils, a 100μsec integrator time constant was selected as being most compatible with the 30μsec discharge current pulse length of the thruster. Table I compares the calibrated response of the Rogowski coils.

Table I   PPT Rogowski Coil Sensitivities with a 100μsec Passive Integrator

Coil Type	Coil Sensitivity, Amp/volt
Main Discharge	25000 ± 3084
Coupling Current	2849 ± 365
Trigger Current	2555 ± 327

18
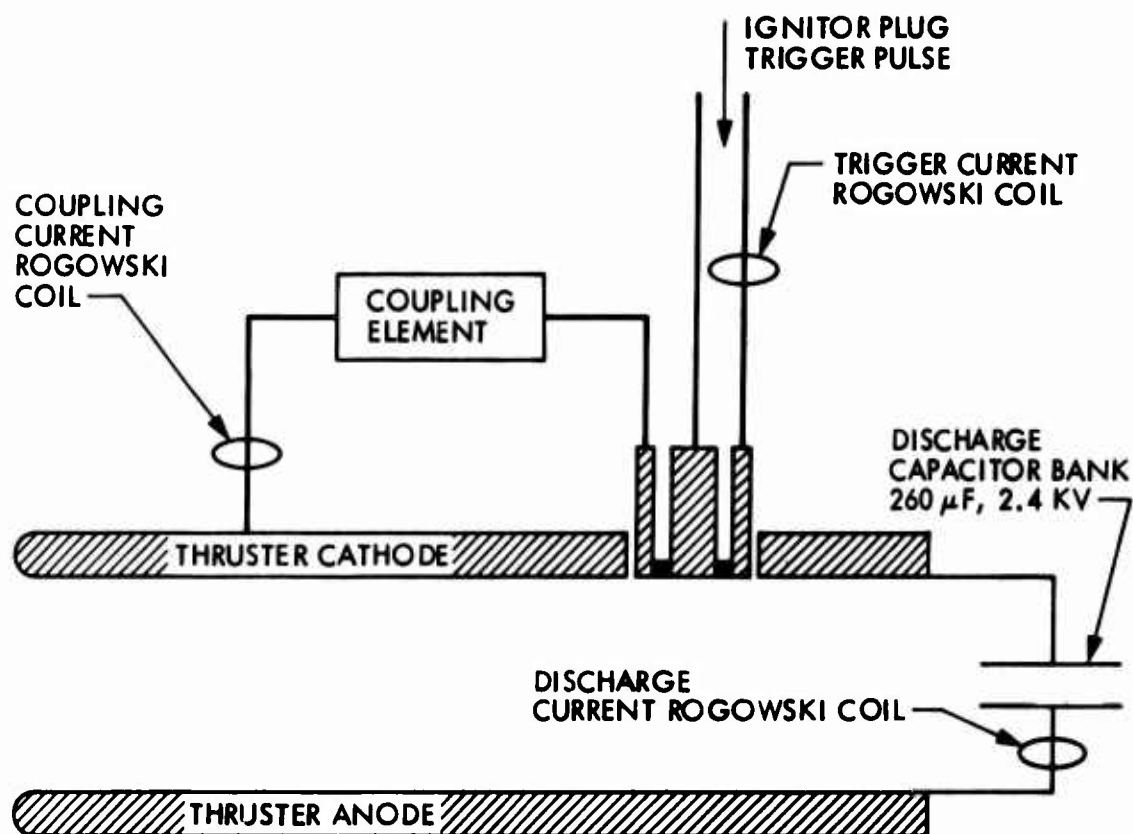
Figure 5. Thruster Rogowski current pickup coil placement.

It should be noted that the tabulated coupling and trigger current Rogowski coil sensitivities differ from sensitivity values reported for these coils during the performance of this work. An error in the analysis of the calibration data for these coils was noted towards the end of the study period. Subsequent to this discovery, these Rogowski coils were recalibrated with the correct coil sensitivities appearing in the above table.

Plug Resistance Measurement Technique:

Several methods were investigated for their effectiveness in monitoring ignitor plug erosion and deposition. These methods ranged from simply weighing the plug before and after each test, to applying highly reflecting gold coatings on the tested plug's face and determining material removal or deposition by Ronchi diffraction methods. For reasons of complexity, cost, or practicability, most of these methods were rejected. The measurement technique finally selected was that of monitoring the resistance of the ignitor plug semiconductor element during each thruster test sequence. This particular approach permitted an accurate qualitative indication of the amount of carbonaceous deposit on the plug face. Since the deposit overlays the ignitor plug semiconducting element tending to short it out, the ignitor plug resistance (measured during those times when the plug is not firing) tends to decrease with an increasing deposit accumulation. Consequently, by monitoring the ignitor plug resistance variation with thruster pulse number, one can tell fairly precisely whether the plug is operating clean or dirty. The merit of this technique, which has been used successfully at the Fairchild Republic Corporation[2], is that plug

20

resistance can be measured external to the vacuum system. In order to determine ignitor plug erosion, a scanning electron microscope was used to examine the ignitor plug face after it was removed from the thruster at the end of each test. Fortunately, the face of an ignitor plug including the carbonaceous deposit was sufficiently electrically conducting so that the application of a thin gold film was not necessary when using the scanning electron microscope. As a result, the same ignitor plug could be used for several different tests.

Thirteen ignitor plugs (ten new and three used) were received from the Fairchild Republic Corporation. Upon receipt, serial numbers were inscribed upon the plug bodies to insure that no mix-ups between plugs would occur. Initially, plug resistance was measured using a Simpson VOM and a General Radio Bridge. It was noted that plug resistance varied markedly from plug to plug and from instrument to instrument. To eliminate this ambiguity, it was decided to adopt a standard plug resistance measurement test circuit utilizing a constant current source. Figure 6 details the main features of this circuit. Briefly, the Fluke calibrator provided a constant current of 0.1 mA with an applied bias of 0 to 50 volts (equivalent to 0 to 500,000 ohms). The Dana DVM permitted tenths of ohms resolution when measuring tens of ohms plug resistance. The tester was a two-wire system, so the resistance of the connecting leads was included in the measured resistance value. The added test lead resistance was a few tenths of an ohm, and was not considered to be significant.

The selection of 0.1 mA as the constant current in the aforementioned

21
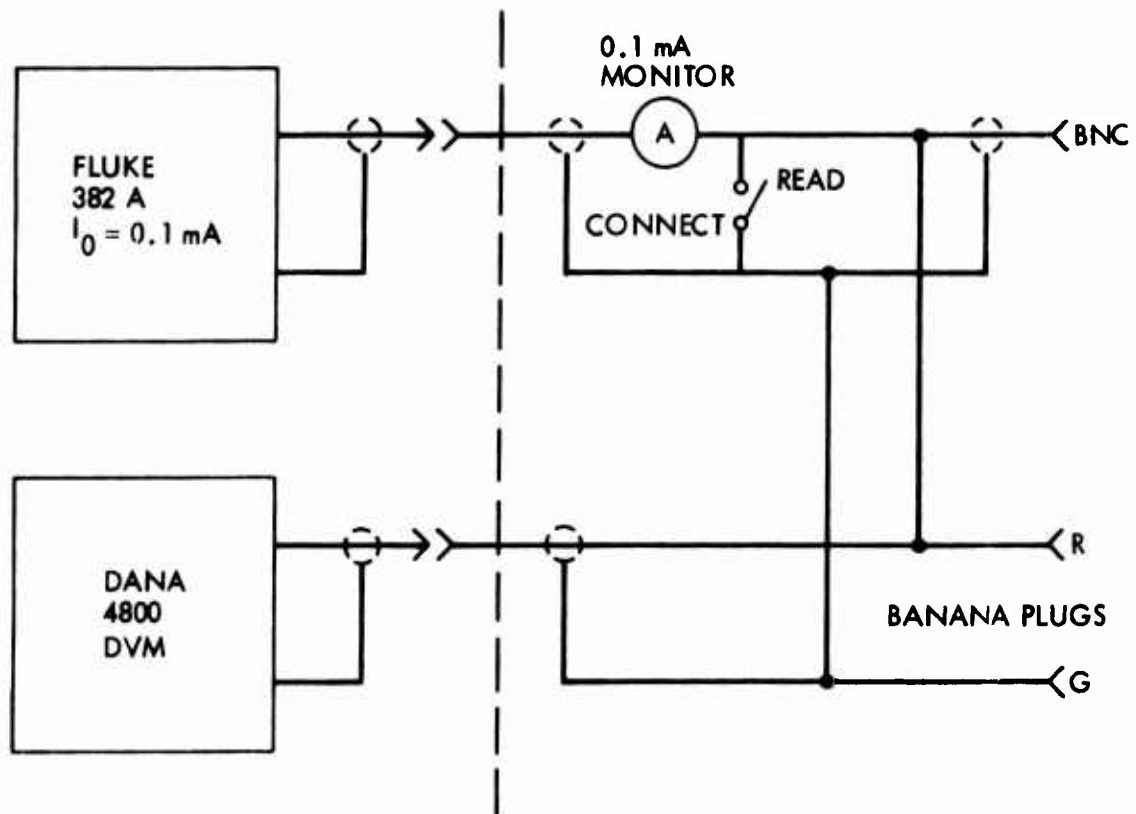
Figure 6. Constant current ignitor plug resistance tester.

22

resistance measuring circuit was made on the basis of thermal consid-
erations. Initial tests indicated that the plug resistance was tempera-
ture sensitive. It was found that larger values of applied current
could heat the plug semi-conductor material sufficiently to cause
drifting resistance readings. Calculations showed that because the plug
semi-conductor layer was so thin ($\sim$0.5 mm) even applied currents as low
as 1.0 mA could result in a significant heat load.

2.2 Coupling Resistance Tests

From observations and conclusions made at the Fairchild Republic
Corporation[2] it was apparent that there must be an optimum amount of
carbonaceous deposit required on the ignitor plug face for reliable plug
operation. It was hypothesized that too much deposit acted as a low
impedance in parallel with the plug semi-conductor element, tending to
short out the plug and resulting in unreliable plug firing. Conversely,
too little deposit meant that the plug microplasma was composed pri-
marily of ablated semiconductor and plug cathode and anode electrode
material, leading to excessive plug wear. Preliminary experiments at
FRC[2] suggested that the amount of plug deposition might be affected by
the value of the resistor used to electrically couple the plug cathode
and discharge cathode electrode. A series of experiments were conducted
at JPL to further investigate this relationship. The results of these
experiments are discussed below.

Ignitor Plug S/N9:

For these tests, coupling resistor values of 0.050Ω, 0.010Ω and

23

0.001Ω were used, in turn, to electrically couple the ignitor plug cathode and thruster cathode. Figure 7 shows the coupling resistor placement, in relation to the ignitor plug housing and coupling current Rogowski coil, all of which are shown positioned above the PPT discharge chamber.

Figure 8 compares the effect of various coupling resistor values, as a function of thruster pulse number on the resistance history of ignitor plug S/N9. Plug resistance measurements were taken at selected times during the test period. The thruster was turned off and the plug was not firing during the time the plug resistance was measured. The results shown in Fig. 8 indicate that varying coupling resistance from 0.050 ohms to a near zero value had a detrimental effect on plug operation. Thruster misfiring became evident when the plug resistance reached about 1.4 ohms. Shortly thereafter, the PPT ceased operating and the tests were terminated.

Altough only approximately 250,000 thruster pulses were obtained with plug S/N9, the plug face was very heavily coated with a carbonaceous deposit. Evidence of the accumulation of deposit on the face of plug S/N9 is shown in Fig. 9. To obtain the scanning electron micrographs shown in Fig. 9, ignitor plug S/N9 was removed from the thruster at the end of each coupling resistance test. These photos show that the thickness and spread of the deposit on the plug face increased in proportion to the number of thruster pulses. Decreasing values of coupling resistance did not serve to reverse this trend. In a similar manner, it can be observed that mild erosion of the plug anode is occurring simultaneously with the heavy deposit build up on the plug cathode and semiconductor. It should be noted that a slot 0.7 mm wide with a depth of 0.5 mm was

24
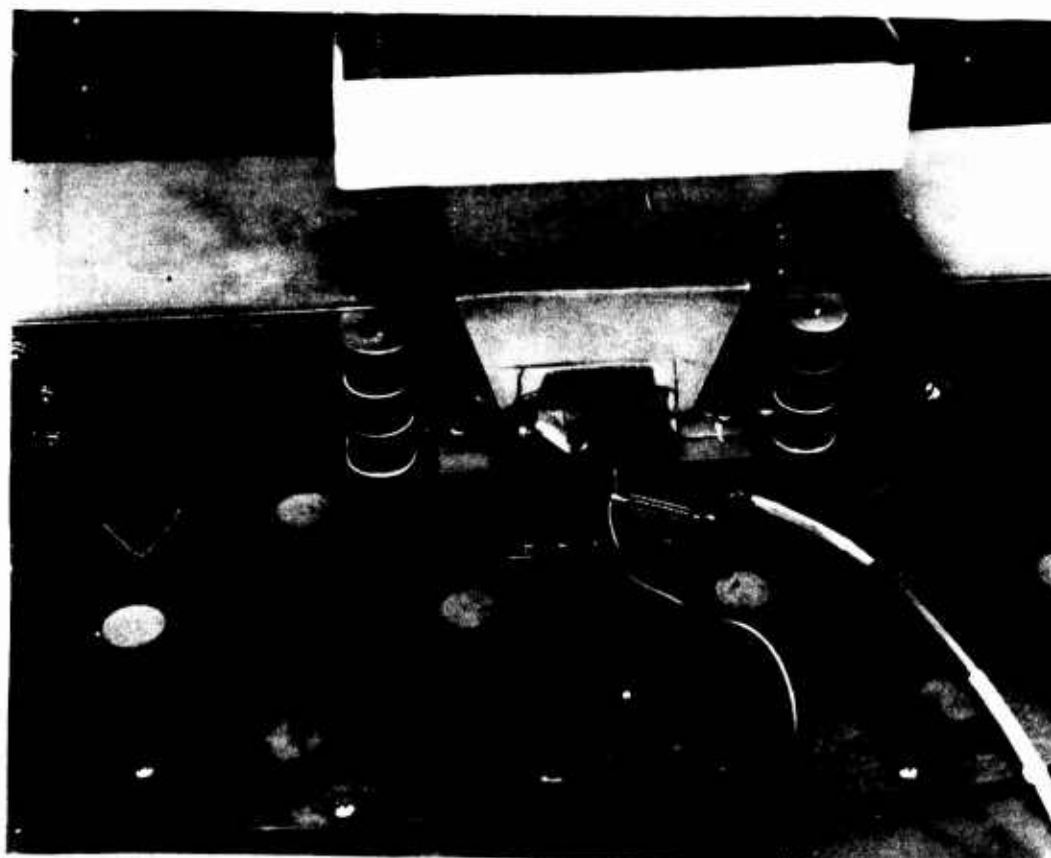
Figure 7. View of PPT discharge chamber showing 0.050Ω coupling resistor.

25
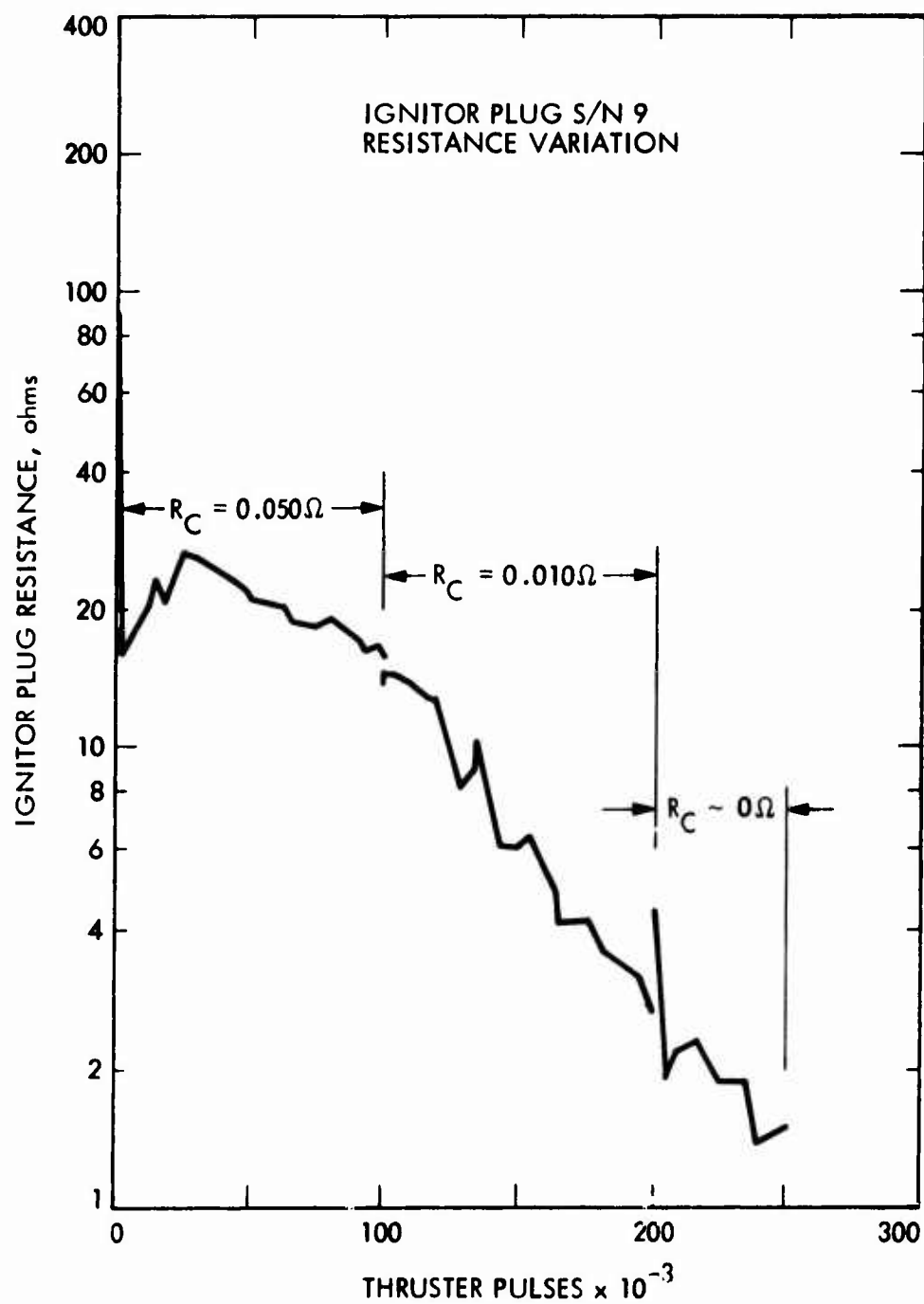
Figure 8. Resistance variation for ignitor plug S/N9.

INITIAL

100,000 PULSES

200,000 PULSES

250,000 PULSES

Figure 9. Deposit accumulation on plug S/N9 with decreasing coupling
resistance and increasing thruster pulse number.

deliberately cut into the face of plug S/N9 prior to the initiation of these tests. This slot provided a reference mark for the scanning electron micrographs and served as a basis by which erosion and deposition of the plug face could be determined.

As the coupling resistance between the plug cathode and discharge cathode was decreased during testing of plug S/N9, the coupling resistor current increased. Peak coupling current values of approximately 1250-2500 amperes were observed for a 0.050 ohm coupling resistance. These peak values increased to approximately 3500-4400 amperes with a shorting wire in place of the coupling resistor. The fact that such large currents were attaching themselves to the ignitor plug and significant deposition still occurred, suggested that it was not feasible to burn off the carbonaceous deposit by intensifying discharge chamber arc attachment to the plug. Rather, just the reverse seemed to happen and it appeared that arc attachment to the plug face was the medium, or mechanism, by which ablated teflon products were transferred to the plug face.

Ignitor Plug S/N2:

At this point in the program, it was decided to investigate a 10.0Ω coupling resistor to determine its effect on ignitor plug resistance and consequently its effect on the carbonaceous deposit accumulation. With a 10.0Ω coupling resistor peak coupling currents were approximately 220 ampere. Figure 10 shows the result of a 160,000 pulse test with ignitor plug S/N2. This test was voluntarily terminated at this time because comparison with the previous tests of plug S/N9 showed a simi-

28
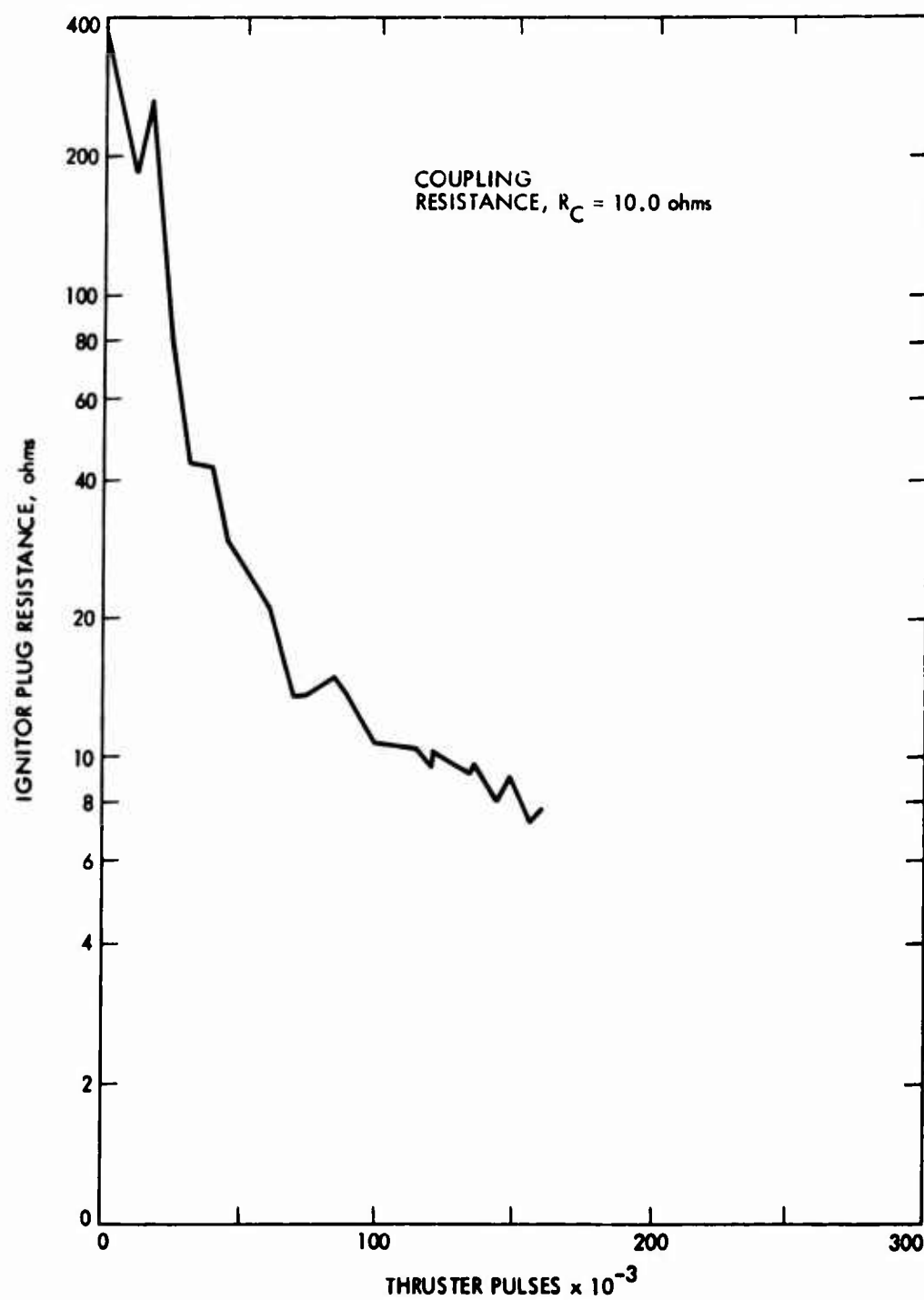
Figure 10.   Resistance variation for ignitor plug S/N2.

lar decreasing resistance trend with increasing thruster pulse number. Removal and inspection of plug S/N2 at the end of the test period showed that its face was only slightly less encrusted with deposit than that of plug S/N9 after a similar number of pulses.

2.3 Summary

The results of the arc cleaning experiments indicated that over the four decade range of coupling resistance values tested (0.001Ω to 10.0Ω) the carbonaceous deposit build up on the ignitor plug face could not be controlled. Moreover, these test results indicated that intensifying arc attachment to the plug face by decreasing coupling resistance to very low values (while still maintaining the vacuum gap between the ignitor plug and surrounding thruster cathode electrode) did not serve to burn off the accumulated deposit. Instead, this arc appeared to play a role in carrying the carbonaceous products to the ignitor plug face. However, the higher 10.0Ω coupling resistance tests, where coupling current or arc attachment to the plug face was significantly less, also produced an unacceptably heavy deposit build up on the plug face. This latter result implied that the large initial rapidly rising coupling current spike, characteristic of a resistive coupling element, might also bear some relationship to the deposit accumulation process on the plug face.

3.0 OPTIMUM COUPLING DETERMINATION

From the results presented in the previous section, it was apparent that the magnitude and perhaps the shape of the coupling current pulse exchanged between the plug cathode and thruster cathode, as a result of discharge chamber arc attachment to the plug face, bore some relationship to the accumulated plug deposit. It was the objective of the optimum coupling determination task to investigate coupling elements other than resistors to determine their effect on ignitor plug deposition and erosion. Concurrent with this study was an investigation of trigger current pulse shapes to determine the effect that this parameter had on plug deposition.

3.1 Coupling Inductance Tests

Effect on Coupling Current:

Following the results of the arc cleaning experiments, it was reasoned that the requirement for minimal plug deposition might be to electrically isolate the ignitor plug as much as possible from interactions with the thruster discharge chamber arc. One method of obtaining this isolation is to use an inductor, with a charging time constant relatively long with respect to the thruster discharge current pulse, in place of the conventional resistance coupling element. Tests were performed with an inductor fabricated on an air core plastic former using #20 AWG stranded copper wire. The inductance of this coil was 142μH with an ohmic resistance of approximately 0.5 ohms. Figure 11 illustrates the variation in the coupling current trace when 0.001Ω and 10.0Ω coupling resistors and the 142μH coupling inductor were used as coupling ele-

31

COUPLING
CURRENT
1425 amp/div. ↑

$5 \mu S$

$R_C = 0.001 \Omega$

COUPLING
CURRENT
142.5 amp/div. ↑

$5 \mu S$

$R_C = 10.0 \Omega$

COUPLING
CURRENT
28.5 amp/div. ↑

$5 \mu S$

$L_C = 142 \, \mu H$
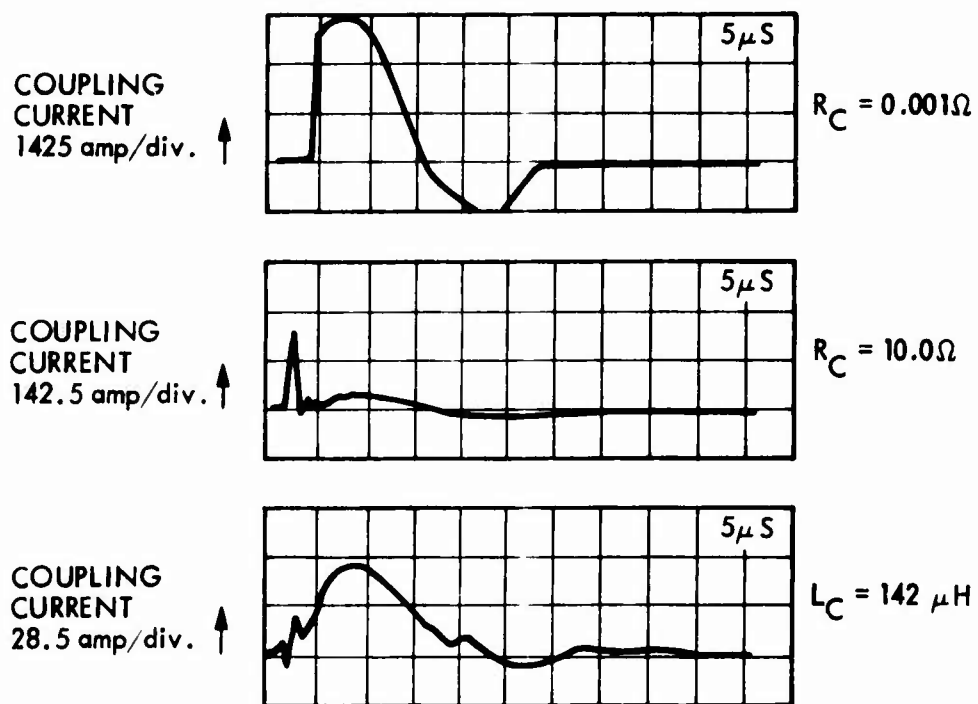
Figure 11. Effect of coupling element on coupling current.

ments. It is noteworthy that a four decade change in coupling resistance produced about an order of magnitude change in peak coupling current. From Fig. 11 it is evident that the coupling inductor with its relatively long charging time constant (284µsec), has effectively damped the coupling current pulse.

Plug S/N1 Tests:

After it became evident that an inductor was capable of keeping the coupling current to low levels and of completely eliminating the large initial current spike to the plug face from the thruster arc, a short life test of 120,000 pulses was initiated. For this test, the 142µH inductor was used as the coupling element and ignitor plug S/N1 was the plug installed in the thruster. Figure 12 shows the results of this life test. For comparison purposes, the resistance variation of plugs S/N9 and S/N2, which used 0.050Ω and 10.0Ω coupling resistors respectively, have been shown also. Figure 12 shows the beneficial effect inductive coupling had on the ignitor plug resistance variation. Using the 142µH coupling inductor, plug resistance stayed approximately constant at 120Ω. Figure 13 compares scanning electron micrographs of the face of plugs S/N 1, 2, and 9. For these photographs, plug S/N 1 had accumulated approximately 120,000 pulses with the 142µH coupling inductor, plug S/N2 had accumulated 160,000 pulses with the 10.0Ω coupling resistor and plug S/N9 had accumulated 100,000 pulses with the 0.050Ω coupling resistor. From Fig. 13 it is evident that the use of a coupling inductor rather than a coupling resistor results in a significant reduction in the amount of carbonaceous deposit accumulated on the ignitor plug face.
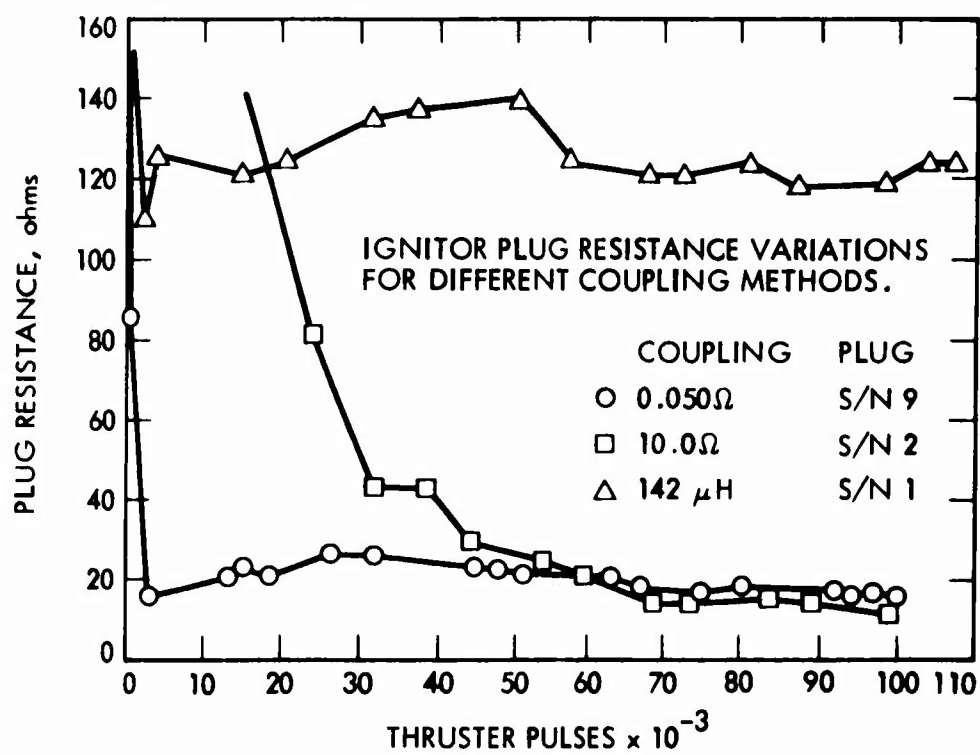
Figure 12. Effect of coupling element on ignitor plug resistance.

142μH
120,000 PULSES

10.0 ohm
160,000 PULSES

0.05 ohm
100,000 PULSES
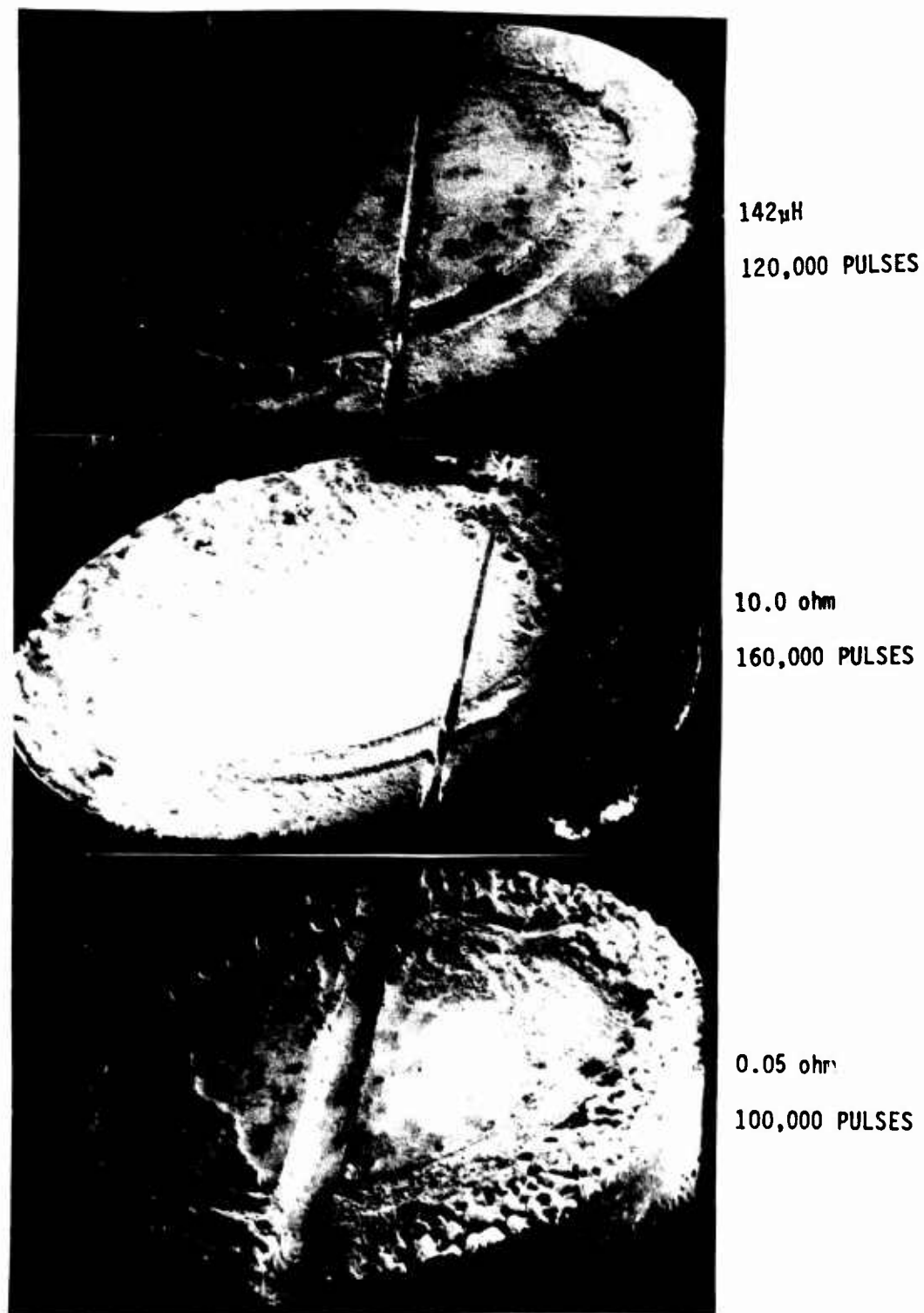
Figure 13.   Effect of coupling element on plug deposit; plug S/N1 top, S/N2 middle and S/N9 bottom.

35

Inductor Selection:

Comparing the results presented in Figs. 12 and 13, it was apparent
that inductive coupling limited ignitor plug deposition and the varia-
tion of ignitor plug resistance. Since both of these phenomena appeared
to be related to the peak coupling current, a range of coupling inductor
values were investigated experimentally to determine their effect on
peak coupling current. Figure 14 shows the results of these tests.
From Fig. 14 it can be seen that increasing the coupling inductance
value much above $100\mu H$ had only a small effect on the peak coupling
current. It should be noted that all the coupling inductors tested in
Fig. 14 were wound to have resistance value of approximately 0.1Ω.
Also, peak coupling currents varied appreciably from pulse to pulse for
each coupling inductor tested. Consequently, the magnitude of the peak
coupling currents presented in Fig. 14 are average values only.

3.2 Trigger Circuit Tests

Conventional Trigger Circuits:

The coupling inductor tests with ignitor plug S/N1 presented in Fig.
12 indicated that inductive coupling was likely to result in a constant
plug resistance at least an order of magnitude larger than typically
obtained with resistive coupling. However, the ignitor plug trigger
circuit used thus far in the experiment had been designed specifically
to fire efficiently heavily deposited ignitor plugs of low resistance
value. Consequently, it was thought that this trigger circuit might not

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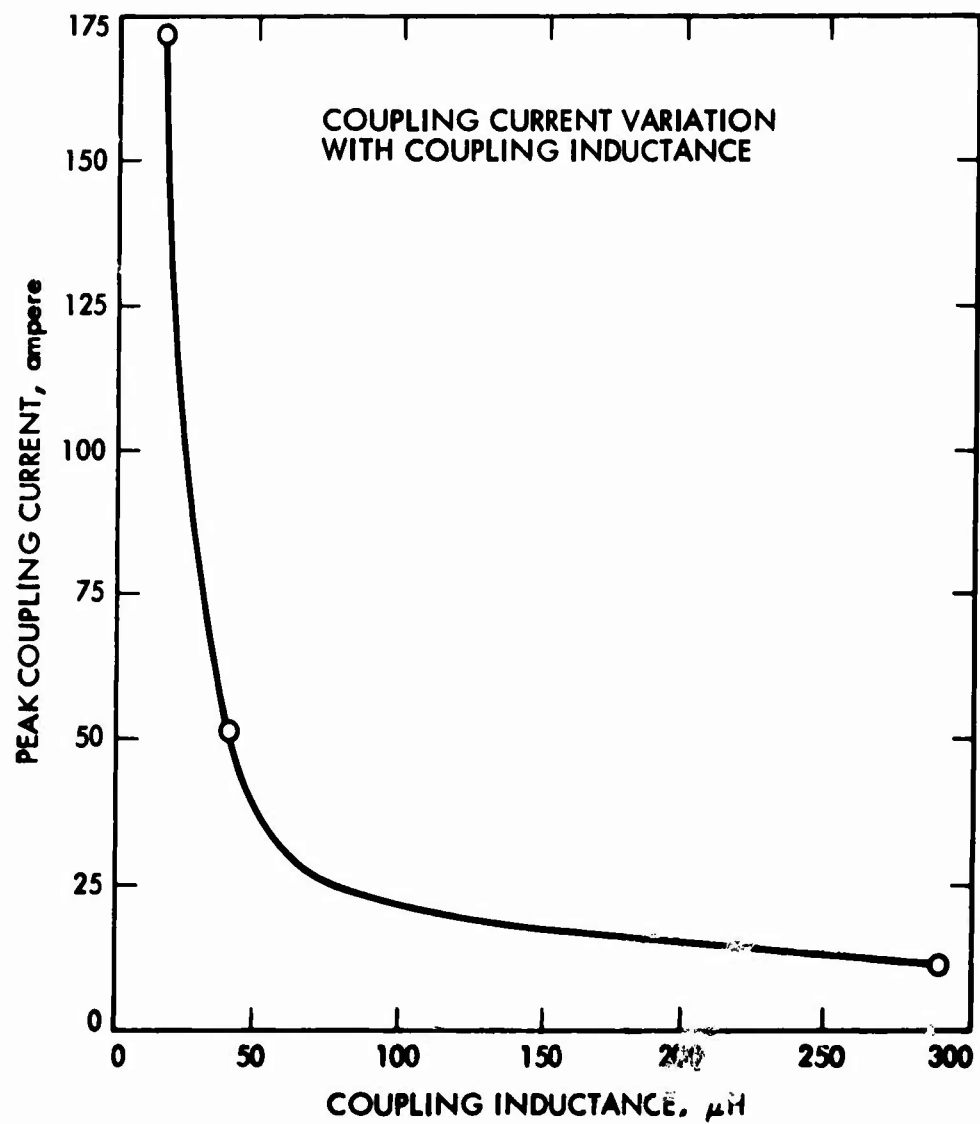
Figure 14. Effect of coupling inductance on peak coupling current.

be appropriate for the cleaner, higher resistance plugs characteristic of inductive coupling. To answer this question, the plug trigger circuit originally developed by Guman[7] for the microthruster, which used a 3:1 step up 1800 volt output impulse transformer, was connected to the thruster and life testing of plug S/N1 was continued.

Use of the 3:1 step up trigger circuit immediately reduced ignitor plug resistance at a rapid rate. After 200,000 pulses with this trigger circuit the resistance of ignitor plug S/N1 had decreased from an average value of 120 ohms to about 20 ohms. Comparing the trigger circuit current pulse from the previously used 1½:1 step down 400 volt output trigger circuit to that of the 3:1 step up 1800 volt output trigger circuit, showed that there was significantly less current flowing from the step up trigger circuit than the step down trigger circuit. It was reasoned that this reduction in trigger circuit current flow decreased the amount of carbonaceous deposit ionized and blown off the plug face during the ignitor plug discharge. This decreased blow off apparently led to an increasing accumulation of deposit on the plug face after each thruster pulse. In an effort to increase the trigger circuit current, two of the 3:1 step up impulse transformers were connected in parallel to produce a higher current 1800 volt pulse. This configuration was then used to trigger plug S/N1 and the thruster discharge for an additional 100,000 pulses. It should be mentioned that the 1½:1 step down, 3:1 step up and dual 3:1 step up trigger circuits used during the testing of plug S/N1 all used an identical amount of trigger circuit capacitor energy storage.

Figure 15 details the resistance variation of ignitor plug S/N1 for

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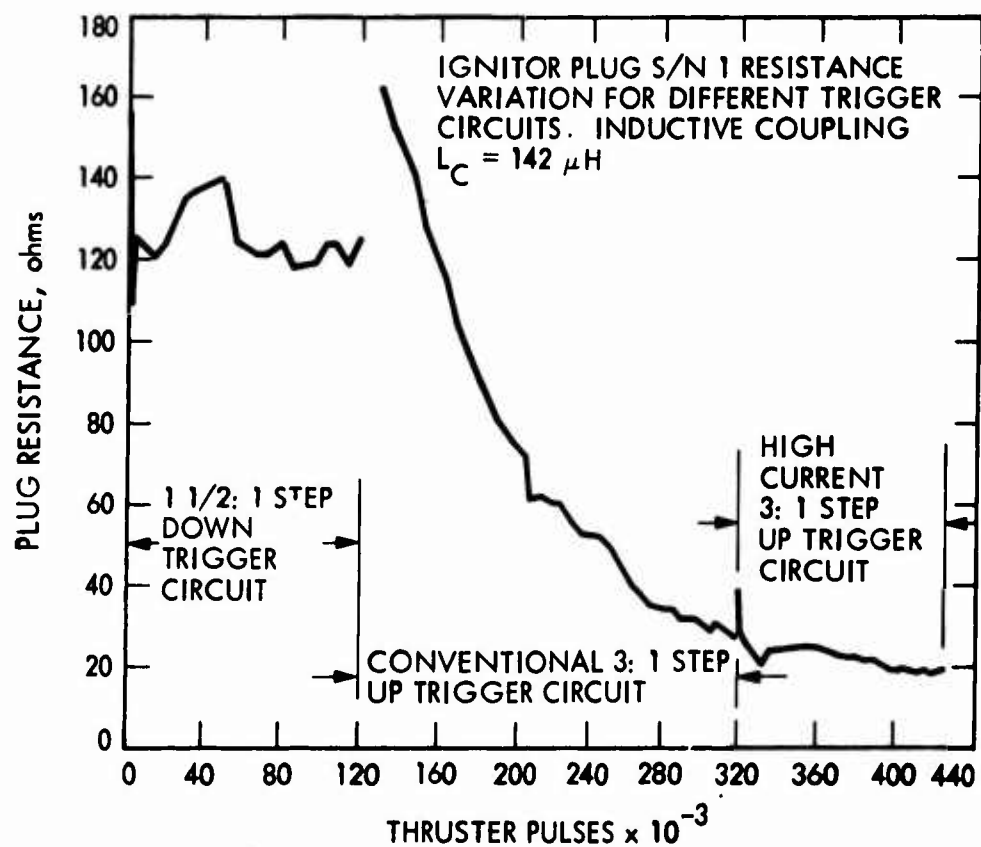
Figure 15. Effect of different trigger circuits on ignitor
plug S/N1 resistance.

each of the three different trigger circuits described above. It would appear from Fig. 15 that the high current, dual 3:1 step up trigger circuit configuration decreased the rate at which plug resistance was declining. The sharp break in plug resistance shown between the termination of plug testing with the 1½:1 step down trigger circuit and the start of the 3:1 step up trigger circuit tests, was a manifestation of removing the ignitor plug from the vacuum environment for a series of scanning electron micrographs. Experience has shown that exposing an ignitor plug to air tends to increase its resistance. However, this effect is temporary and returning the plug to a vacuum environment, with continued plug operation, quickly reconditions the plug to its previous resistance trend. Presumably, this behavior is a result of water absorption on the plug face and/or atmospheric chemical modification of the ever present carbonaceous deposit as suggested by Palumbo and Begun.[2] During testing of the 3:1 step up trigger circuits shown in Fig. 15, the ignitor plug was not exposed to the atmosphere and this is why no large break in resistance is apparent.

Thruster Repair:

The life test of plug S/N1 using the paralled 3:1 step up trigger circuit was involuntarily terminated after a thruster storage capacitor failure. Upon dismantaling the thruster, two of the thruster energy storage capacitors were found to have leaked oil. The worst of these capacitors was replaced by a new unit while the other leaky capacitor was repotted with epoxy. Both capacitors were vacuum leak tested before installation in the thruster. At this time, the thruster was refueled with new teflon fuel bars except those at the rear of the discharge

40

chamber (i.e., closest to the energy storage capacitors). These rear
fuel bars had not been consumed to the same extent as the other fuel
bars and it was sufficient to remachine their faces.

Experimental Trigger Circuit:

The test results presented in Fig. 15 suggested that the trigger
circuit current level was important in the control of the carbonace-
ous deposit accumulated on the face of an ignitor plug in a one-milli-
pound pulsed plasma thruster. Examination of the plug discharge current
pulses characteristic of the 1½:1 step down, 3:1 step up and dual 3:1
step up trigger circuits showed that these current pulses typically
had pulse lengths on the order of the main thruster arc pulse length
($\sim$ 30μsec). Since an ignitor plug discharge was necessary only to
fire the thruster, an effort was made to reduce the trigger circuit
pulse length to as short a time as possible. By doing this, the
trigger circuit current would be increased, assuming the trigger cir-
cuit stored energy was held constant. Also a shorter plug pulse length
would provide more isolation of the ignitor plug discharge processes
from these processes occurring in the thruster arc. It quickly became
apparent that the type of impulse transformers normally used in
pulsed plasma thruster trigger circuits were not capable of the short
pulse widths being sought. A coaxial impulse transformer design was
ultimately used because this design was capable of very short pulse
widths and was easy to fabricate. The design selected used a 1:1 turns
ratio with an input voltage of 2000 volt. Due to the high voltage,
two methods of switching were investigated. One method used two 1200
volt silicon controlled rectifiers (SCR) in series while the other
method used a single Kryton cold cathode gas filled switch

41

tube. Figure 16a documents the experimental trigger circuit design
showing the Kryton tube switching method. Also included in Fig. 16a
is a schematic diagram of the conventional 1½:1 step down trigger
circuit. Typical trigger circuit current pulses for the two switching
methods are presented in Fig. 16b. For comparison, the current trace
from the 1½:1 step down trigger circuit is also shown. All the current
pulses in Fig. 16b were obtained with the trigger circuits firing
ignitor plug S/N7 during normal thruster operation.

Plug S/N7 Tests:

A new life test was initiated using ignitor plug S/N7 and the coaxial
impulse transformer trigger circuit designs discussed above. Initially,
plug S/N7 was operated for 100,000 thruster pulses using the experimen-
tal trigger circuit design with the twin SCR switching method. These
tests were terminated at the end of this period because of an SCR failure.
Several new pairs of SCR's were then tested. However, all these fur-
ther attempts to pair up SCR's failed during a standard twenty four hour
bench test of these circuits. At this time, the Kryton switching ap-
paratus was installed in the trigger circuit and the tests were resumed.
However, the inherently shorter lived Kryton tube lasted only 50,000
thruster pulses before it too failed. A new Kryton tube was installed
after this failure but this tube lasted only an additional 70,000
thruster pulses before it also failed. In spite of these circuit ele-
ment failures, the overall test results were encouraging. Figure 17
shows that the resistance of plug S/N7 was increasing throughout these
tests (to minimize the plug deposition caused by large coupling cur-
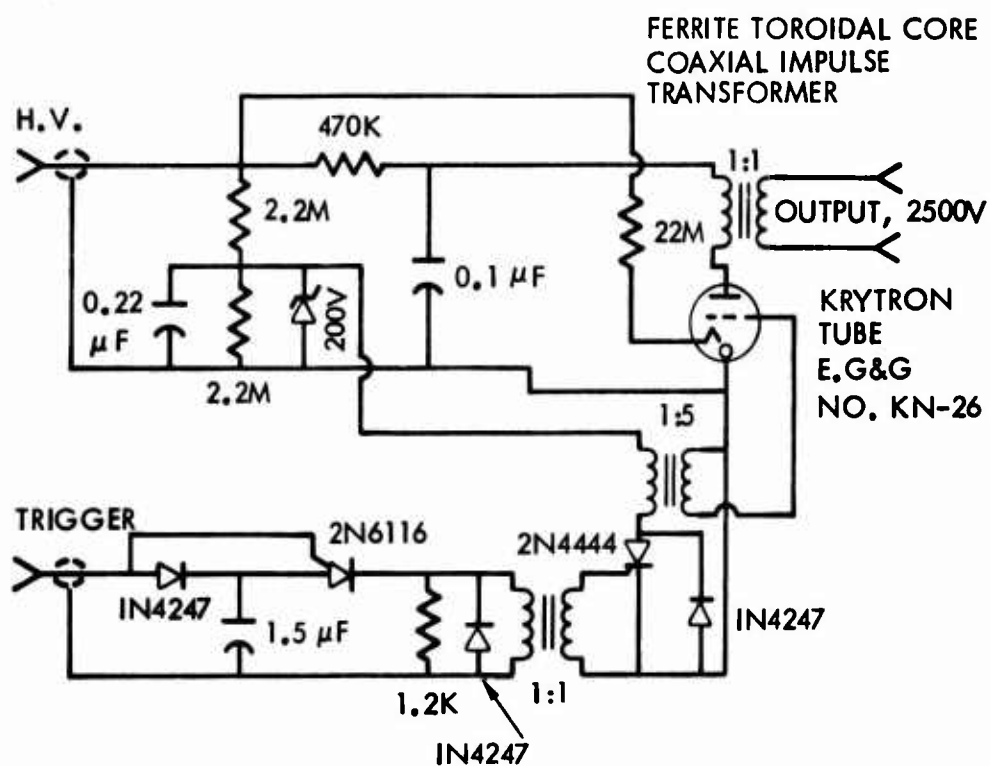rents, a 288μH coupling inductor was used). At the time of the SCR

42
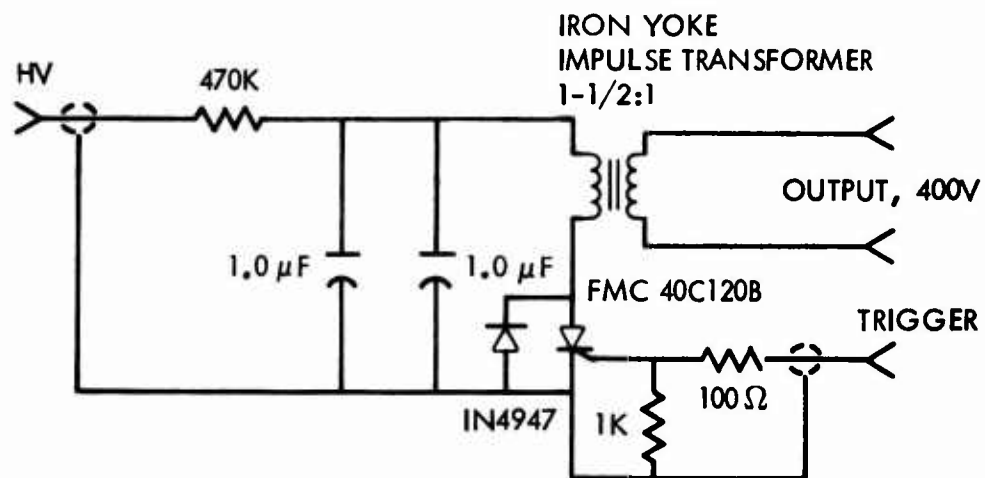
Figure 16a. Comparison of conventional (top) and experimental (bottom) trigger circuits.

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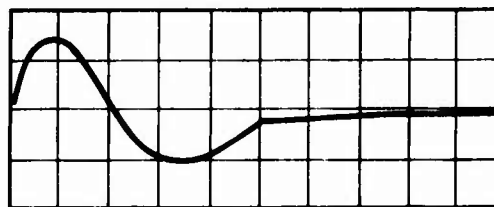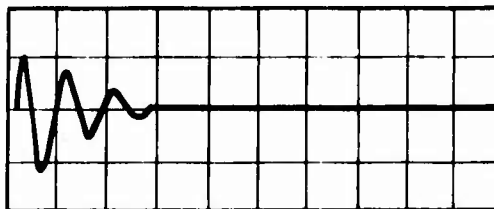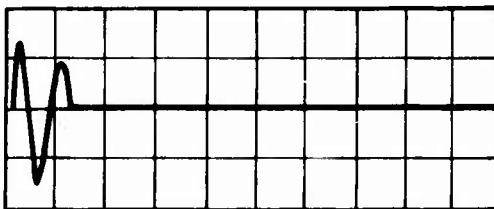
Figure 16b. Effect of different trigger circuit designs on trigger current pulse width.

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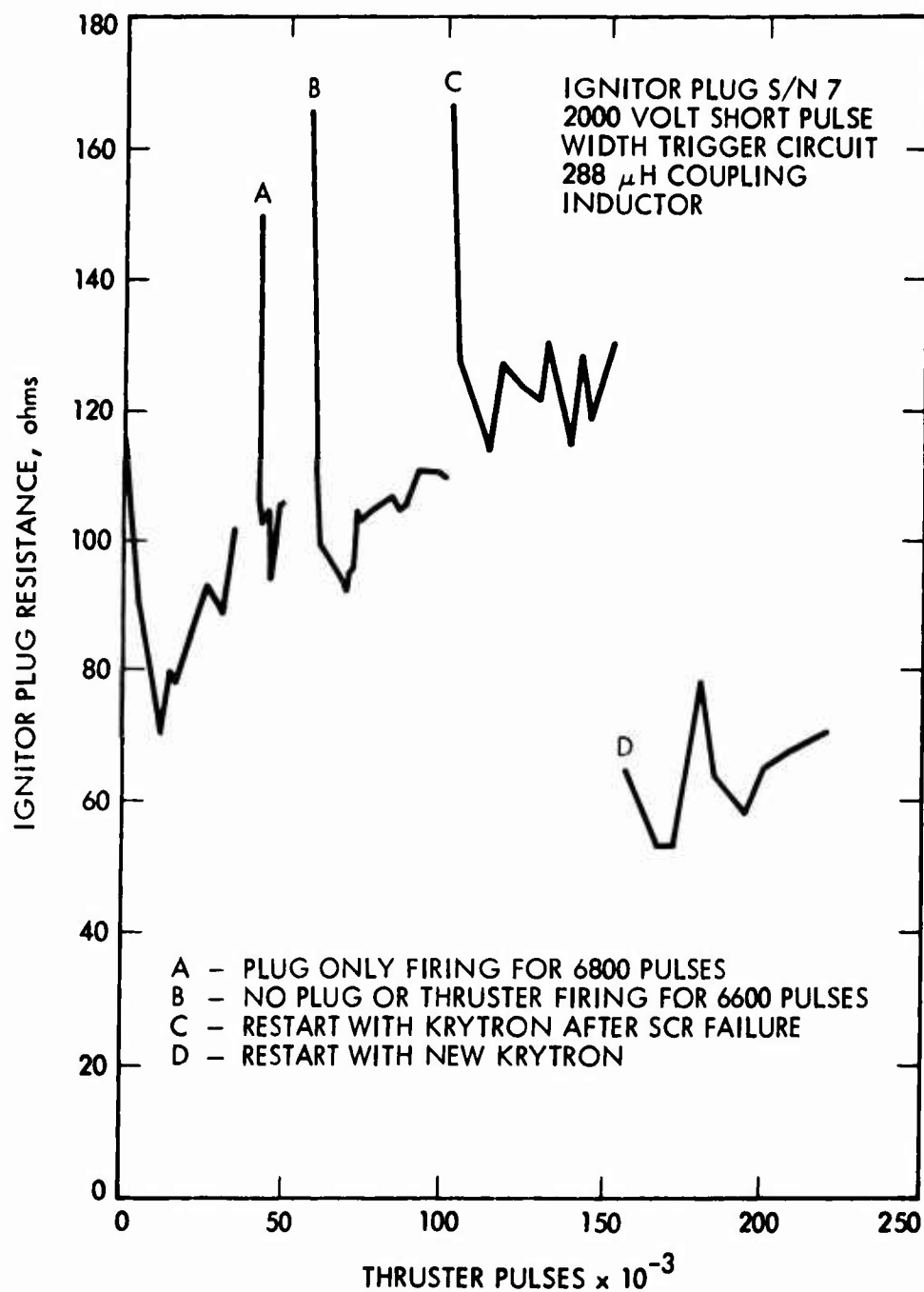
Figure 17. Resistance variation for ignitor plug S/N7 using
the experimental trigger circuit and a
288 μH coupling inductor.

45

failure the plug was inspected visually. The plug face was found to have a shiny appearance with only slight deposit accumulation. Points A and B in Figure 17 pertain to logic upsets in the thruster control circuitry which caused power supply but not vacuum system shutdown. The failure mechanism of the Kryton tube was such that it began firing the plug very rapidly. As a result of this rapid firing, an essentially sustained arc was produced within the thruster discharge chamber for several minutes before the failure was detected and thruster shutdown effected. This arc produced a lot of carbonaceous deposit on the plug face and this is why the plug resistance at point D started at a low value. It is noteworthy that the average plug resistance from this point onward still seemed to be increasing.

Thruster Repair:

Life testing of ignitor plug S/N7 was involuntarily terminated after approximately 225,000 pulses because of a sustained arc which developed between the thruster anode and cathode electrodes. Complete disassembly of the entire thruster was necessary before the cause of the arc break-down problem could be identified. The problem was finally traced to decomposed mylar insulating sheets that separate and insulate the large copper anode and cathode current collector plates tying together the thruster energy storage capacitors. Figure 18 shows the decomposed mylar strip line insulator sheets. It is beleived that outgassing from the edges of these mylar sheets created a Paschen breakdown pressure region which allowed the strip line ends to arc over. This arcing effectively destroyed the mylar sheets and produced conducting carbon tracking across the strip line phenolic insulating surfaces. It is

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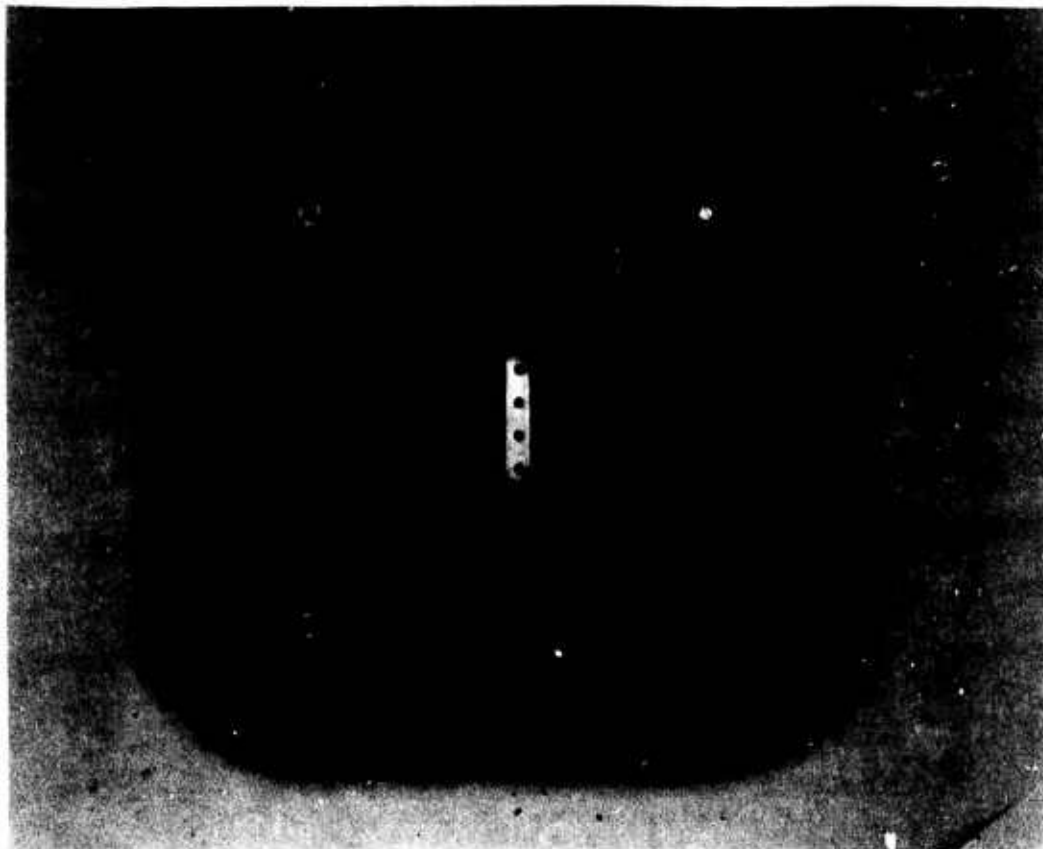
Figure 18. Decomposed mylar strip line insulator.

47

speculated that this problem had been in existence for some time and had gradually gotten worse until all insulating parts were sufficiently conducting to support a sustained arc.

The damaged mylar insulator sheets were replaced by two sheets of 0.13 mm thick Kapton. These kapton sheets were not glued together as had apparently been done to the mylar sheets. Also, the cathode current collector plate was modified to create a longer insulating path length between it and the anode plate where these plates were connected to the thruster electrode strip lines. To permit more complete thruster outgassing, several holes were punched in the thruster back plate and covered with stainless steel mesh. Following these thruster modifications, a new series of tests were initiated with ignitor plug S/N8. For these tests, the experimental trigger circuit used a $0.1\mu F$ storage capacitor and an EG&G model No. KN-26 Kryton switch tube. This switch tube was an improved version of the Kryton tubes used during life testing of plug S/N7. A $288\mu H$ coupling inductor was in use for these tests.

Plug S/N8 Tests:

The object of the test program using plug S/N8 and the $288\mu H$ coupling inductor was to determine the effect experimental trigger circuit stored energy had on the ignitor plug resistance variation. Consequently, the life test was started with a relatively low trigger circuit voltage of 1500 volt which corresponded to a stored energy of only 0.11 joule. With this configuration, plug resistance dropped very rapidly with

48

thruster pulse number. After 66,000 pulses the measured plug resistance was only 12Ω. At this time, the trigger circuit voltage was increased to 2000 volts which corresponded to a stored energy of 0.20 joule. As expected, the trigger current amplitude increased, but after an additional 18,000 thruster pulses the trigger current was again low. During operation at 2000 volts, the plug resistance could not be measured because of a siezed relay inside the vacuum tank. Because of the low trigger current at 2000 volts, the trigger voltage was increased to 2500 volts. After about an additional 20,000 thruster pulses, the seized relay was finally cleared. The measured plug resistance at this point was 7.8Ω. The plug resistance varied between 7.7 and 8.0Ω for an additional 100,000 thruster pulses before the test was involuntarily terminated because of a sustained thruster arc.

In total, about 200,000 thruster pulses were accumulated with plug S/N8. The test results indicated a minimum experimental trigger circuit stored energy of 0.31 joule, corresponding to a trigger circuit voltage of 2500 volts was necessary to stabilize the ignitor plug resistance variation and consequently the ignitor plug deposit acculmulation. Upon removal of the ignitor plug for inspection, it was felt that the plug face had considerably more deposit on it than would have been expected with the experimental trigger circuit and coupling inductor used. Some of this deposit had a varnished appearance quite unlike that normally seen on ignitor plugs at the end of other life tests. An analysis was performed on this deposit and showed it to consist of elements common to a nearby discharge chamber insulator made of vespel material. This insulator had been installed around the plug housing at the start of the tests with plug S/N8 after the original boron nitride insulator had been broken. It was speculated that the thruster plasma environment decom-

49

posed the vespel and that the vaporized products found their way to the plug face. Because of this, it was felt that the tests of plug S/N8 were done in an environment more conducive than normal to the accumulation of discharge chamber products on the plug face. The particular insulator was subsequently remade from mykroy material.

Thruster Repair:

As mentioned previously, the thruster experienced a sustained arc which terminated testing of plug S/N8. Upon disassembly of the thruster, it was found that the kapton insulating sheets between the large copper strip line plates above the thruster energy storage capacitors had degraded and arced over. Compounding the Kapton insulator failure was significant oil leakage from two of the energy storage capacitors. This oil had seeped into the space between the Kapton sheets and had migrated along these sheets to the region where the copper strip line plates made connections to the thruster cathode and anode strip lines. Both of the oil leaking capacitors were removed from the thruster and replaced by new capacitors which had previously been epoxy potted and vacuum leak tested. The decomposed Kapton insulating sheets were replaced by a single 1.5 mm thick teflon sheet. Also, critical regions on the phenolic insulators used to separate the small strip lines feeding the cathode and anode electrodes from the large copper strip line plates were wrapped with Kapton tape as an extra measure of arc-over protection.

3.3 Ignitor Plug Erosion and Deposition

Plug Embrittlement:

Throughout the PPT ignition study, a consistent effort was made to examine all the ignitor plugs used before, during, and after the various test programs in order to determine those erosion mechanisms acting to degrade the plug face. Perhaps the most obvious plug erosion mechanism encountered during this test program was the plug embrittlement problem. After the resistive coupling tests of plug S/N9 (Fig. 9), this heavily deposited plug was cleaned of deposit on its face by using a high speed nylon brush. The results of this cleaning operation were unexpected. Beneath those areas where carbonaceous deposit lay on the plug face the base material was embrittled and flew off in small chunks as the rotary brush was applied. Figure 19 compares the cleaned face of plug S/N9 to the uncleaned face of this plug at the end of the test period shown in Fig. 9. The relationship between the carbonaceous deposit buildup and plug embrittlement is striking. Most of the embrittlement has occurred on the plug cathode (outer ring in Fig. 11) where the deposit was heaviest. It is interesting to note that on those areas where no deposit lay, only the slightly textured appearance reminiscent of plasma sputtering is evident.

An analysis of the deposit on plug S/N9, and on other plugs used during this test program, was performed by the Surface Science Laboratories of Palo Alto, California. These analyses showed the deposit to be a very complex fluorocarbon with small amounts of incorporated oxygen. The carbon/fluorine ratio of this deposit was 1.1 which was significantly more than the C/F ratio of 0.5 for the virgin teflon used

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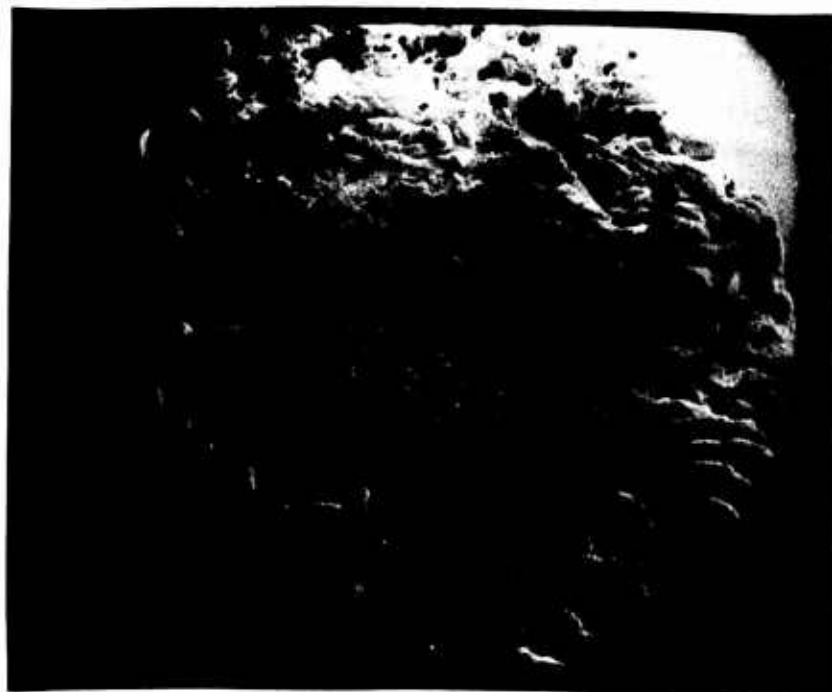
Figure 19. Face of ignitor plug S/N9 before (top) and after (bottom) cleaning showing embrittlement.

52

as the thruster fuel bars. Analysis of the ignitor plug face immedi-
ately below the carbonaceous deposit showed a higher proportion of
carbon with a C/F ratio of 2.7. Some of the fluorine on the plug was
found to exist as F^- and to be in good electrical contact with the
metals making up the ignitor plug (the plug cathode is inconel while the
plug anode appears to be Kovar). Other tests on the deposit that nor-
mally accumulates on the copper thruster electrodes indicated the
presence of copper fluorides with a F/C ratio of about 1.2. From these
test results it appears that the cause of the plug embrittlement phe-
nomena may be fluorine chemical attack of the base metals composing the
ignitor plug and/or the formation of brittle metallic carbides.

Plug Erosion:

It was realized early in the ignition study that reducing the amount
of plug deposition and consequently the amount of plug embrittlement
(since the two do seem to be directly related), was very important so
that the more subtle effects of plasma sputter erosion would not be
completely masked. The test sequence using plug S/N7 described earlier
(Fig. 17) represented a situation where ignitor plug deposition was
minimized. Inspection of plug S/N7 provided some estimation of ignitor
plug plasma sputter erosion. Figure 20 shows the face of ignitor plug
S/N7 after its surface had been cleaned with a nylon brush at the end of
the test sequence documented in Fig. 17. For comparison with plug S/N7,
ignitor plug S/N3 which was fired for approximately the same number of
pulses and trigger circuit energy in a small vacuum bell jar, is shown
also in Fig. 20. As mentioned in an earlier section, ignitor plug S/N7
had very little deposit on its surface. This is clearly evidenced by
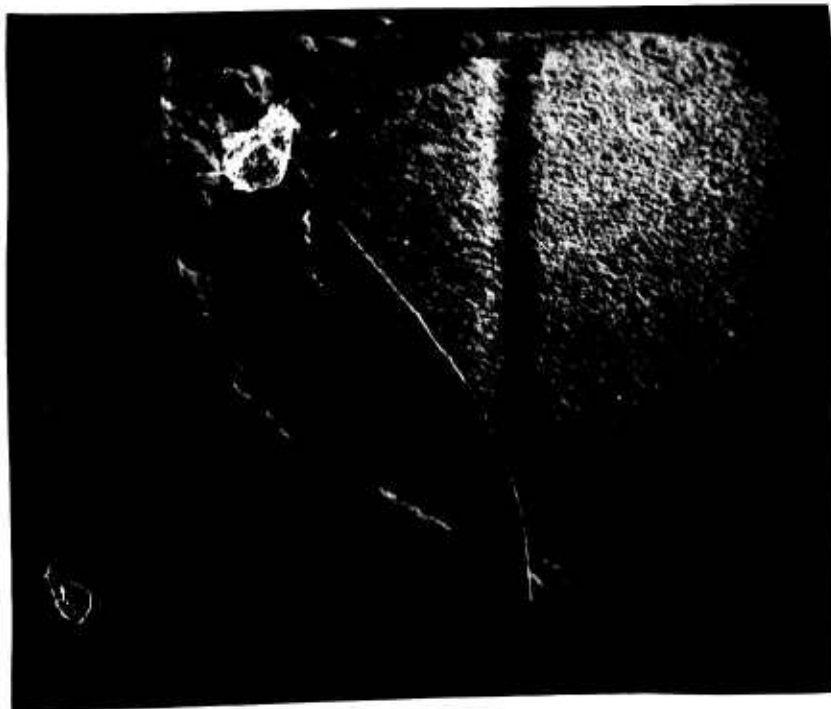
Figure 20. Plug S/N7 (top) showing little embrittlement and
plasma sputter erosion. Plug S/N3 (bottom) showing
damage caused by clean vacuum operation.

the small amount of plug embrittlement that is seen on the plug face. The lightly textured appearance all over the plug face is probably a result of plasma sputter erosion. That this erosion process was not as devastating as the embrittlement phenomenon is apparent by the presence of a groove still evident across the plug anode. This groove was cut to an average depth of 0.05 mm across the plug anode when the plug was new. Figure 20 shows also that a plug used to fire a thruster erodes quite differently from one fired alone in vacuum. Plug S/N3 in Fig. 20 shows severe anode melting and complete vaporization and removal of a large amount of semiconductor and cathode material. Clearly the presence of a small amount of deposit on plug S/N7 was significant in preventing most of the damage caused by the trigger circuit current pulse that occurred with plug S/N3. This result reinforces the contention of Palumbo and Begun[2] that a small amount of deposit on the plug face is necessary to absorb the otherwise severely erosive effects of the ignitor plug discharge.

3.4 Summary

The results of the optimum coupling determination experiments show that inductively coupling the ignitor plug cathode to the thruster cathode is more beneficial to ignitor plug longevity than resistive coupling. These benefits arise from the ability of a coupling inductor to dampen out arc attachement to the ignitor plug face from the thruster discharge (previously described arc cleaning experiments indicated that this arc attachment might be the cause of excessive ignitor plug deposition). A decrease in the amount of plug deposition was also demonstrated through the use of an experimental plug trigger circuit which produced

55

large plug discharge currents and very short pulse lengths. In addition, ignitor plug erosion was shown to occur simultaneously with the accumulation of a carbonaceous deposit on the plug face. Most of this erosion was from an embrittlement phenomenon which could be related directly to the amount and location of a carbonaceous deposit and may be caused by chemical attack of the plug case metals. A lesser amount of erosion occurred from normal plasma sputter processes and a still lesser amount was caused by plug vaporization from the trigger circuit plug discharge current pulse.

4.0 IGNITOR SYSTEM ANALYSIS

During the investigation of the effect various trigger circuit con-
figurations had on ignitor plug performance, it became apparent that the
dynamics of the ignitor plug discharge were important in controlling the
accumulation of deposit on the plug face. To further understand the
characteristics of the ignitor plug discharge, a series of experiments
were initiated to determine the ignitor plug discharge energy and dy-
namic impedance, the plug discharge shot to shot repeatability and the
physical extent and velocity of the ignitor plug plasma plume. Separate
from these experiments was a spectroscopic study of the ignitor plug and
pulsed plasma thruster discharge to determine if spectral line intensity
ratios could be used to qualitatively determine ignitor plug erosion.

4.1 Plug Discharge Energy and Impedance

Analysis Procedure:

Since no data was found to exist that described the dynamic impedance
and energy of an ignitor plug discharge, it was necessary to devise an ex-
periment to measure these parameters. Figure 21 describes an experimental
arrangement that was used to measure plug discharge energy and impedance.
Figure 22 shows typical ignitor plug voltage and current traces recorded
on a dual beam oscilliscope for an ignitor plug firing in the thruster.
These oscilliscope traces were analyzed numerically by first tracing
their waveforms on fine grid graph paper. Once this was done, values of
voltage V, and current I, were determined from the traces at equal
increments of time ($\Delta t = 0.11 \mu sec$). Figure 22 illustrates values of

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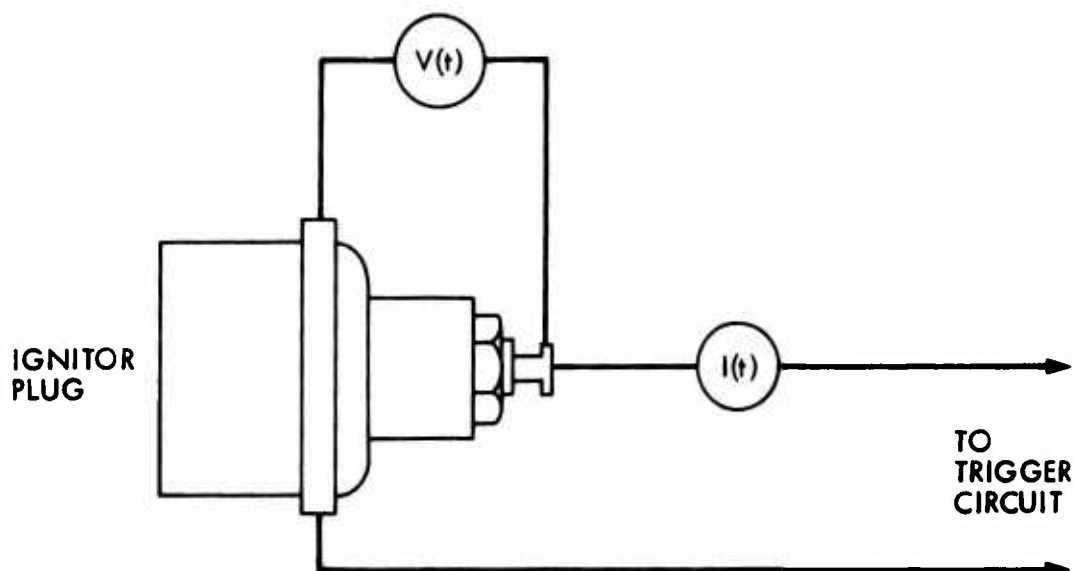
V(t) — RECORDED BY HIGH VOLTAGE PROBE ON ONE
BEAM OF A DUAL BEAM OSCILLOSCOPE

I(t) — RECORDED BY ROGOWSKI COIL ON THE OTHER
BEAM OF A DUAL BEAM OSCILLOSCOPE

FROM SIMULTANEOUSLY TRIGGERED V(t) AND I(t)
TRACES PLUG IMPEDANCE R(t) AND ENERGY E(t) ARE
CALCULATED BY THE FOLLOWING RELATIONS

$$R(t) = \left. \frac{V(t)}{I(t)} \right|_{t = t_i}$$

$$E(t) = \left(\frac{V(t_2) I(t_2) + V(t_1) I(t_1)}{2} \right) (t_2 - t_1)$$

WHERE $(t_2 - t_1)$ << PLUG DISCHARGE PULSE LENGTH

Figure 21. Plug discharge energy and impedance calculation procedures.
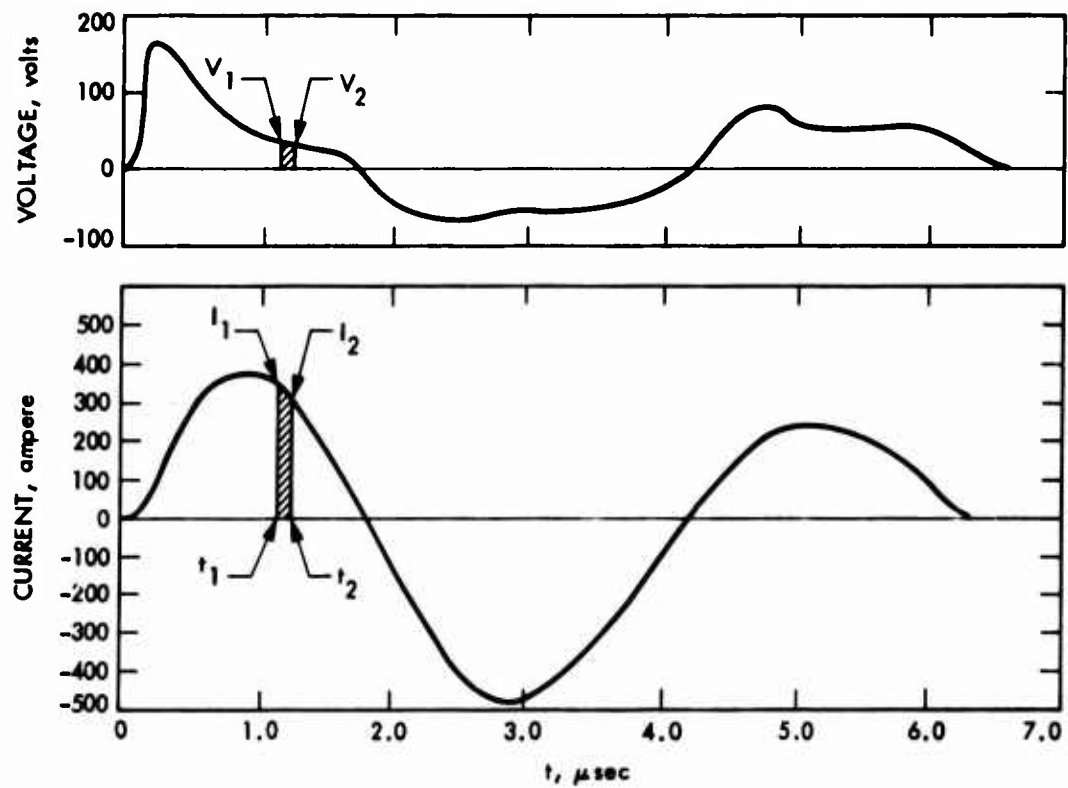
Figure 22. Oscilloscope trace integration procedures for typical plug current and voltage waveforms.

V and I determined over the interval $t_2 - t_1 = \Delta t$. After a table of V and I values had been obtained, the appropriate division and numerical integrations necessary to evaluate $R(t)$, $E(t)$ and the total discharge energy per plug pulse were performed.

The largest single source of experimental error in determining dynamic plug impedance and energy was in ensuring that only the voltage drop $V(t)$ across the ignitor plug, less any voltage drop across the trigger circuit current carrying leads, was recorded. It was observed that even one inch of included trigger circuit lead length gave a detectably different $V(t)$ signal. For bell jar testing where a single ignitor plug was fired in vacuum, the ignitor plug cathode was held at ground potential and plug voltage $V(t)$ was measured using a Tektronix 10:1 high voltage divider probe. This probe was connected directly to the plug anode pin with the ground lead soldered to the plug cathode. For dynamic impedance and energy measurements of ignitor plugs under test in the pulsed plasma thruster, two Tektronix 1000:1 high voltage divider probes were used. These probes had their input terminals connected to test leads soldered to the plug anode and cathode electrodes. The voltage signal from these probes was sensed with a differential pre-amplifier in the oscilliscope.

Energy and Impedance Results:

Figure 23 shows a plot of the calculated energy and impedance variation for the current and voltage trace shown in Fig. 22. This particular trace was of ignitor plug S/N6 operating in the thruster during an extended life test (Section 6 of this report discusses the results of this life test).
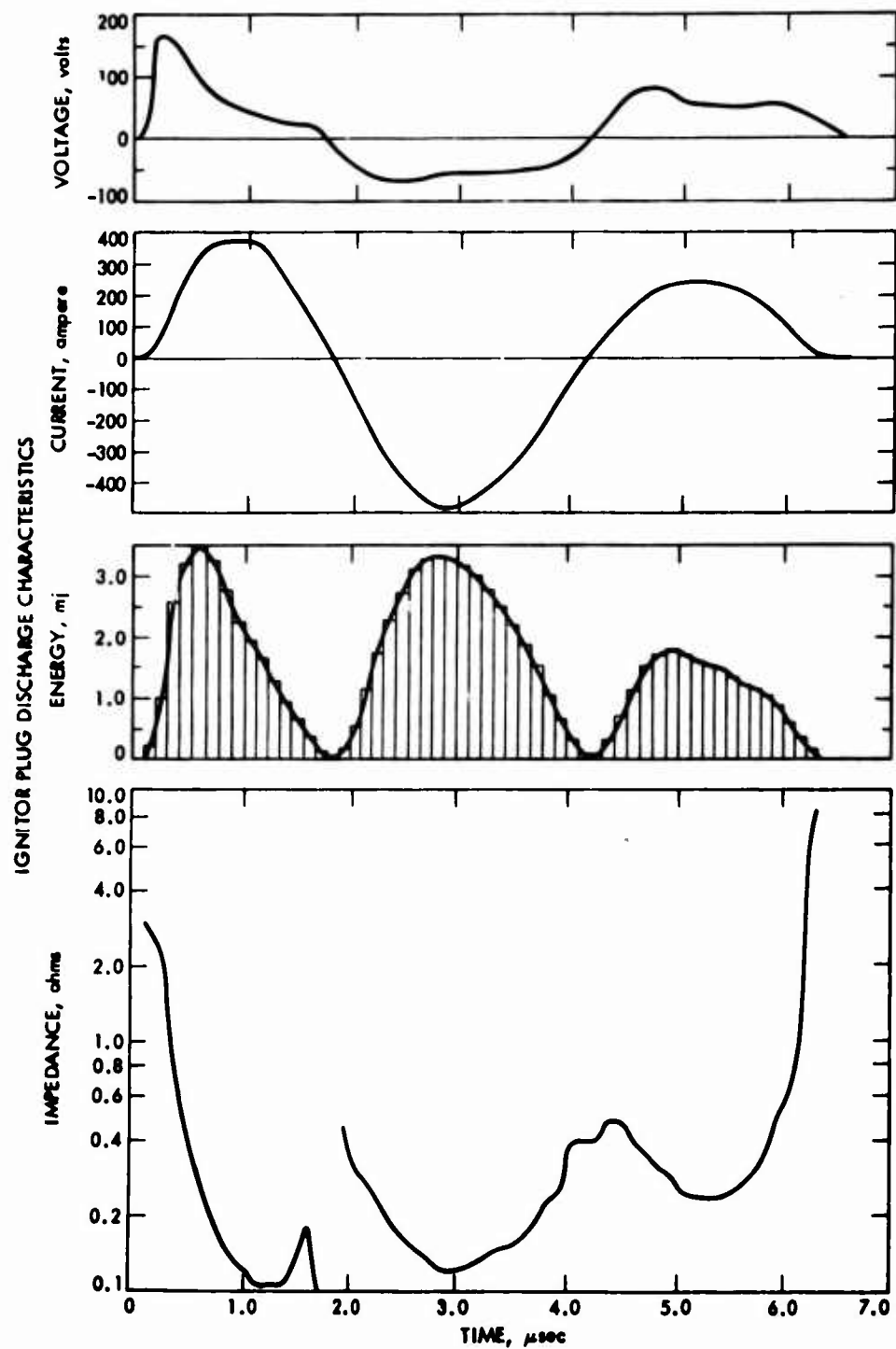
Figure 23. Typical plug discharge energy and impedance variations.

In Fig. 23 the average energy values have been plotted as histograms with a continuous line drawn through these values only to facilitate comparison with the other curves. By summing these average energy values the percentage of energy transferred from the trigger circuit to the plug discharge was obtained. For the experimental trigger circuit, typically 10-20% of the available energy was consumed in the plug discharge. This energy transfer ratio was typically 25-35% for the 1½:1 step down trigger circuit. It was noted that the lead length between the trigger circuit and ignitor plug had an effect on the energy transferred to the plug discharge. Unfortunately, all the testing carried out during the ignitor plug ignition study had the trigger circuit and ignitor plug separated by several feet of connecting wire. It was felt that a much higher energy transfer ratio could be obtained if the experimental trigger circuit were reduced to a single circuit board. This circuit board could be hardwired into the thruster body enclosure so that only a couple of inches of lead length separated the plug and trigger circuit.

Figure 23 also shows a logarithmic plot of ignitor plug discharge impedance as a function of discharge time. It can be observed from this figure that ignitor plug resistance ranges from approximately 0.5 - 0.1 ohm during the peaks in plug discharge energy. This behavior was typical of the many plug discharges that were analyzed in this manner. Although not presented here, it was also observed throughout this investigation that initial ignitor plug resistance, measured during those times the plug was not firing using the circuit shown in Fig. 6, did not have a significant effect on the dynamic plug impedance or energy trends presented in Fig. 23. It appeared that once plug break-

down had been effected, the energy and impedance characteristics of the plug discharge were fairly reproducable, i.e., the plug discharge shot-to-shot characteristics were repeatable.

4.2 Plug Breakdown Characteristics

After the differential voltage probes were installed on the thruster ignitor plug, as described above, it was observed that there was some correlation between ignitor plug breakdown voltage and trigger circuit voltage. Specifically, it appeared that as the trigger circuit voltage was increased, a given ignitor plug would breakdown at a lower applied voltage. It seemed reasonable to assume that increasing the trigger circuit voltage, for a constant trigger circuit capacitance, would result in an increasing rise time in the voltage applied to the ignitor plug. A series of experiments were initiated to determine the effect of applied plug voltage rise time on plug breakdown voltage. The data for these experiments were taken by recording dual beam oscilliscope traces of plug voltage and current for different trigger circuit voltage levels. These traces were obtained at an oscilliscope sweep speed of 200 nsec/cm and it was possible to discern the plug breakdown voltage by determining that point where a sharp rise in plug current was observed. Similarly, the applied plug voltage rise time was calculated by measuring the slope of the rising voltage trace which was usually fairly linear. Figure 24 shows a typical plug current and voltage trace and the geometrical construction used to determine the voltage rise time and plug breakdown voltage. In Fig. 24, the experimental trigger circuit had a trigger capacitor voltage of 2KV.
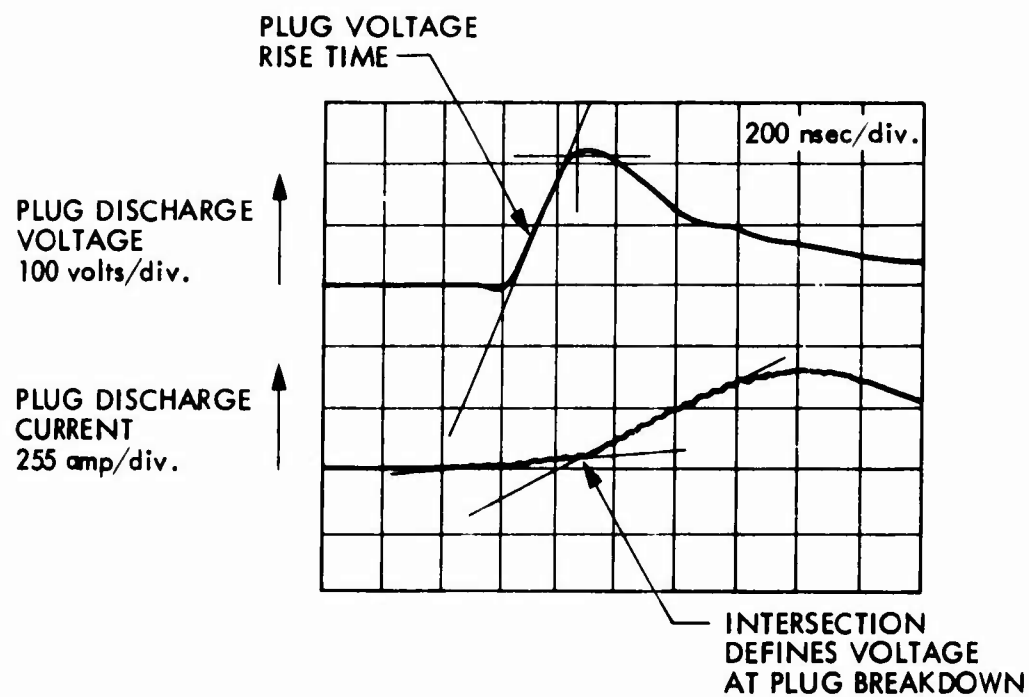
63

Figure 24. Plug voltage breakdown and voltage rise time
analysis technique.

Several determinations of plug voltage rise time and plug breakdown voltage were obtained using ignitor plug S/N6 fired in air and in vacuum with two trigger circuit types. Figure 25 shows the correlation between voltage rise time and breakdown voltage for these different conditions. Here, the 3:4 trigger circuit designation pertains to the conventional 1½:1 trigger circuit in which the normally paralled impulse transformer secondary windings were put in series to provide a slight step up voltage. This was necessary because the 1½:1, 400 volt output, winding configuration would only fire the clean, high resistance plug S/N6 intermittently. The data presented in Fig. 25 shows that there is a strong correlation between increasing plug voltage rise time and decreasing plug breakdown voltage. The effect of firing the plug in air appears to be only that much higher breakdown voltages are required for similar applied voltage rise times. Presumably, this is a result of the good insulating properties of air at ambient temperature and pressure. Above 2000 volts on the experimental trigger circuit storage capacitor, it was observed that vacuum plug operation resulted in a sudden trans- ition to a decreasing plug voltage rise time and plug breakdown voltage. A similar effect was not observed for plug operation in air with this circuit where a fairly linear trend is evident to the 3000 volt trigger circuit test point. Inspection of the ignitor plug current and voltage traces for air and vacuum operation showed that for vacuum operation there was a much greater initial plug conduction current prior to breakdown than for air operation. This suggests some sort of gas or vapor release process upon the application of energy to the plug. Such a local pressure increase could cause a low current discharge to occur on the plug face prior to arc breakdown when the plug is operated in a vacuum environment. This initial current drain could act to depress the

65
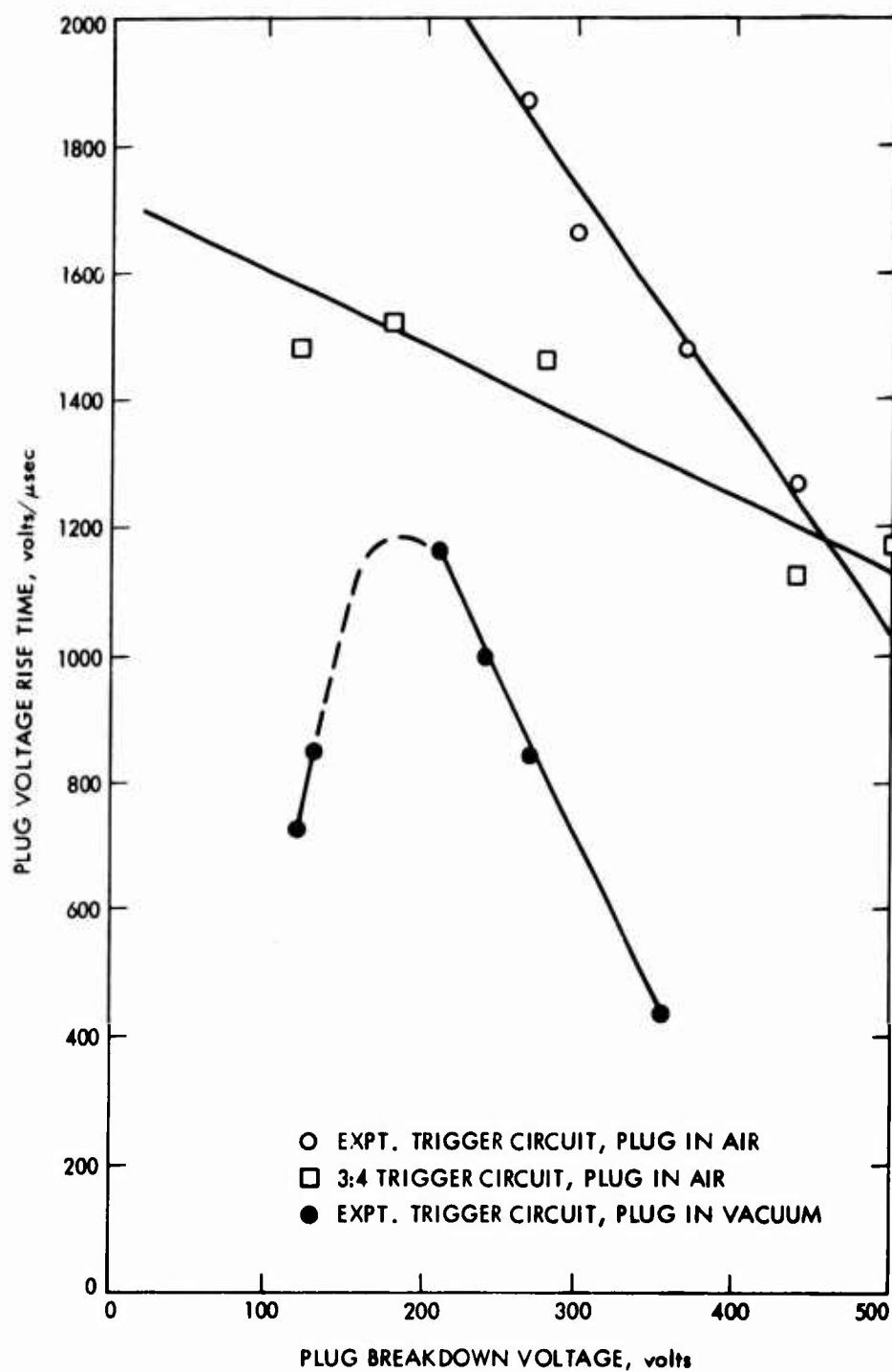
Figure 25. Correlation of plug voltage rise time and
breakdown voltage.

voltage applied to the ignitor plug from the coaxial impulse trigger circuit transformer. Figure 26 compares current and voltage traces for plug operation at 3000 volts trigger potential in air and vacuum and shows the initial current pulse characteristics peculiar to vacuum operation.

4.3 Spectroscopic Tests

Throughout the course of the ignition system study, an effort was made to monitor light emission from the pulsed plasma thruster and ignitor plug discharges. The intended aim of this effort was to identify spectral lines whose intensity was a function of ignitor plug erosion and/or deposition. It was then intended to use variations in these observed intensity ratios to monitor, in situ, ignitor plug erosion and deposition behavior. This ultimate aim was not achieved due to great difficulty in accurately labeling ignitor plug discharge emission lines. However, those results that were obtained and the experimental techniques used during this effort are worthy of some discussion.

Thruster Discharge:

Figure 27 shows schematically the experimental arrangement used to monitor the light emission from the pulsed plasma thruster discharge. In the arrangement used, light from the thruster discharge chamber was collected in a viewing tube through a quartz window at the top of the 1.8 x 3.0 m vacuum tank. This light was then reflected from a front surfaced mirror through a quartz lens which focused the light onto the

67

PLUG IN VACUUM

PLUG DISCHARGE
VOLTAGE
100 volts/div.

PLUG DISCHARGE
CURRENT
255 amp/div.

PRE-BREAKDOWN
CURRENT SLOPE

200 nsec/div.

PLUG IN AIR

PLUG DISCHARGE
VOLTAGE
100 volts/div.

PLUG DISCHARGE
CURRENT
255 amp/div.
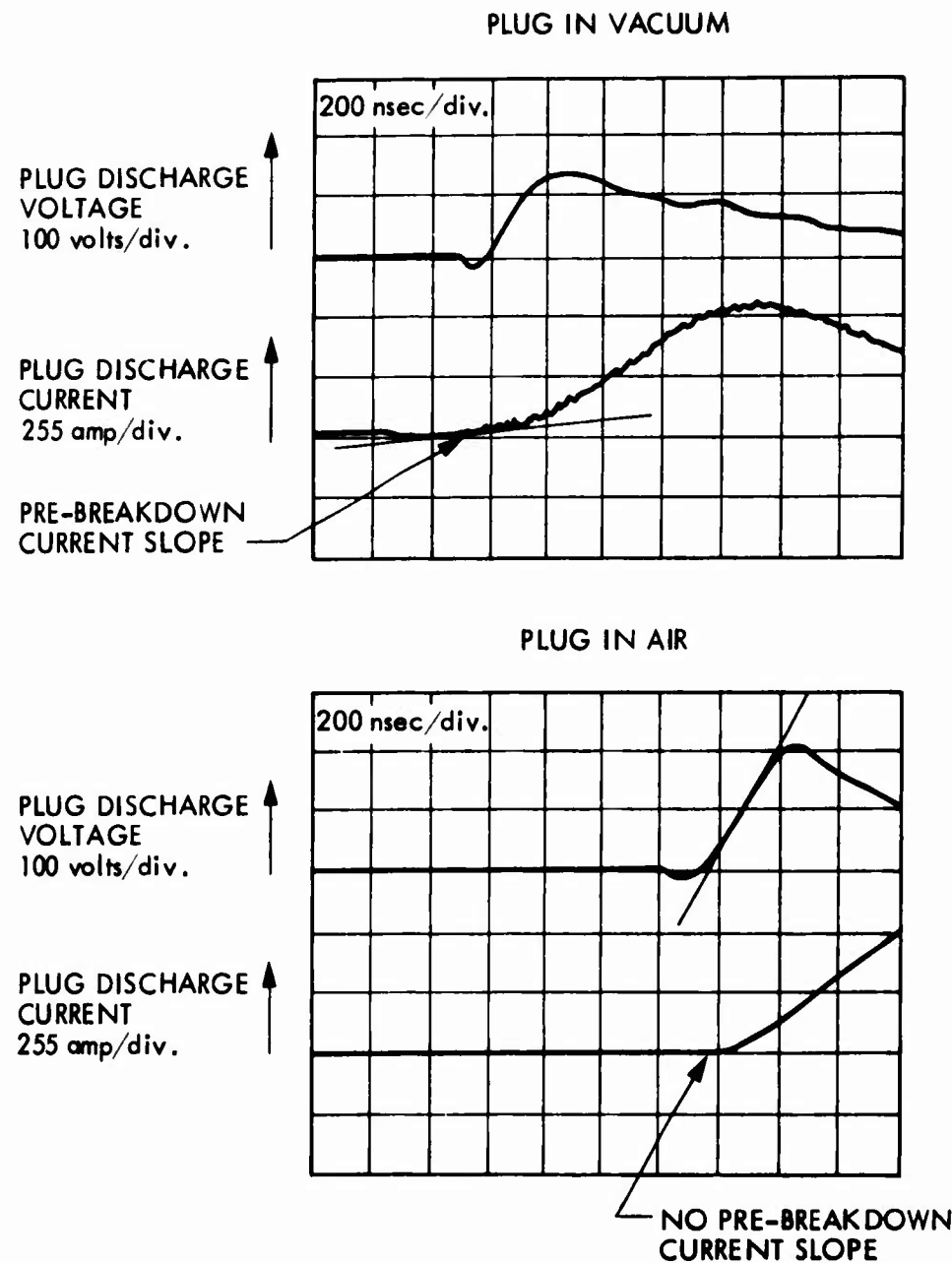
200 nsec/div.

NO PRE-BREAKDOWN
CURRENT SLOPE

Figure 26. Comparison of initial plug breakdown current characteristics
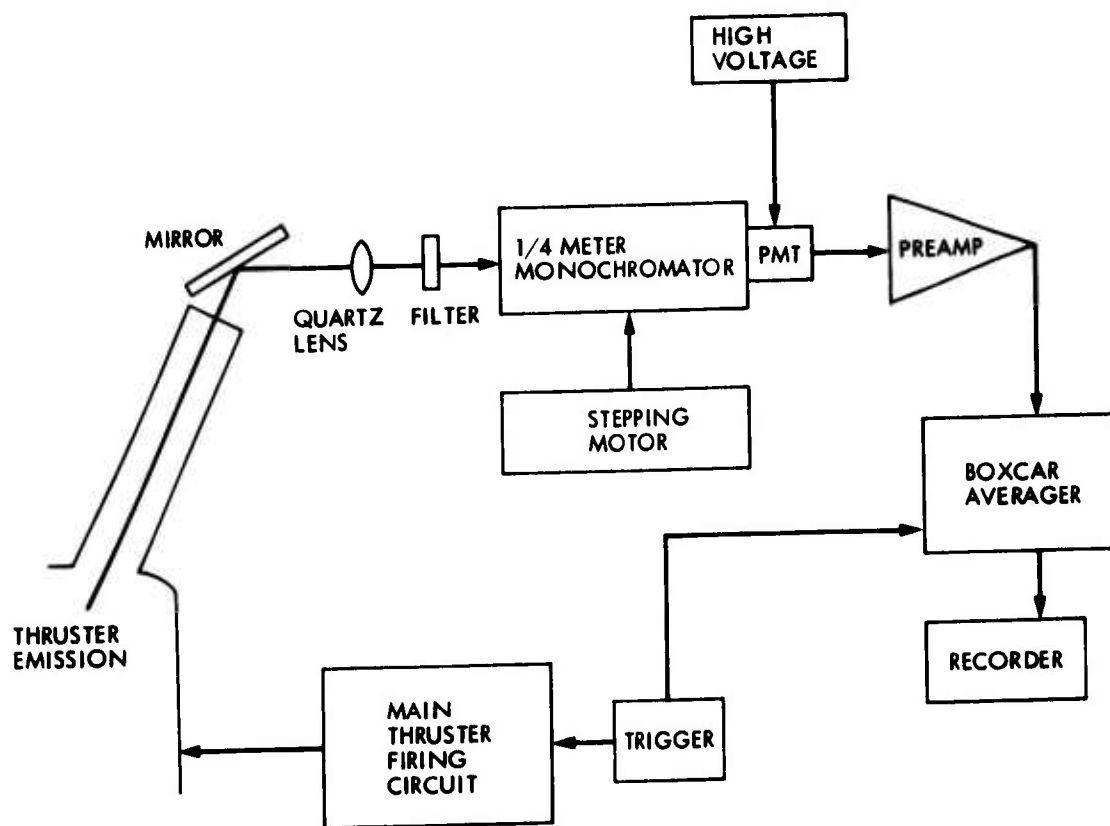for air and vacuum operation.

68

Figure 27. Monochromator arrangement for analysis of pulsed
plasma thruster emission.

entrance slit of a monochromator after passage through a neutral density filter. An instruments SA 0.2m monochromator with ±0.25nm resolution was used to identify the spectral lines. Although of modest accuracy, this instrument was nevertheless very versatile and being small and portable was ameanable to rapid set up and position changes.

Using the apparatus shown in Fig. 27, complete spectral scans, during normal thruster operation, were obtained over the wavelength interval from 300 - 700nm. For these data, only light from a 1μsec wide gate passed into the box car averager. This gate was placed to sample the light from the rising portion of the thruster discharge current pulse just after the thruster arc had been initiated. Figures 28a and b show the results of a typical spectral scan. From these figures it is apparent that there are very highly excited carbon and fluorine species present in the thruster discharge chamber. It should be stressed that the spectral line assignments made in Fig. 28 are tentative only. Equipment more accurate than that illustrated in Fig. 27 would be required to eliminate any ambiguity in a particular emission line and to help identify those lines not labeled in Fig. 28. Nevertheless, the results presented in Fig. 28 do illustrate that it is possible to obtain good repeatable line spectra from the discharge chamber arc of the pulsed plasma thruster.

Ignitor Plug Discharge:

Bell jar tests using the equipment shown in Fig. 27 were also performed in an effort to characterize the light emission from an ignitor plug firing in vacuum. For these tests the light from the
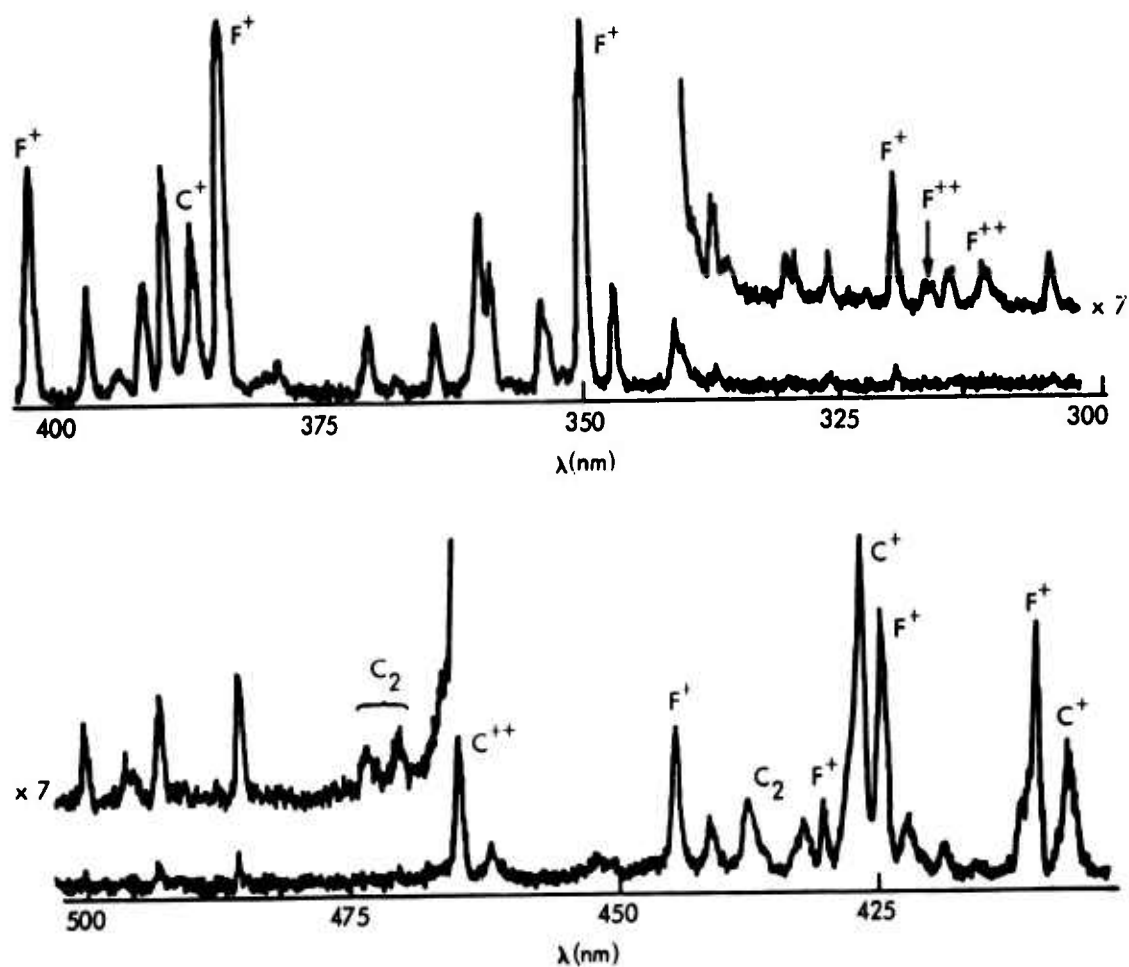
70

Figure 28a. Pulsed plasma thruster discharge chamber emission spectra and tentative assignments, 300-500 nm.
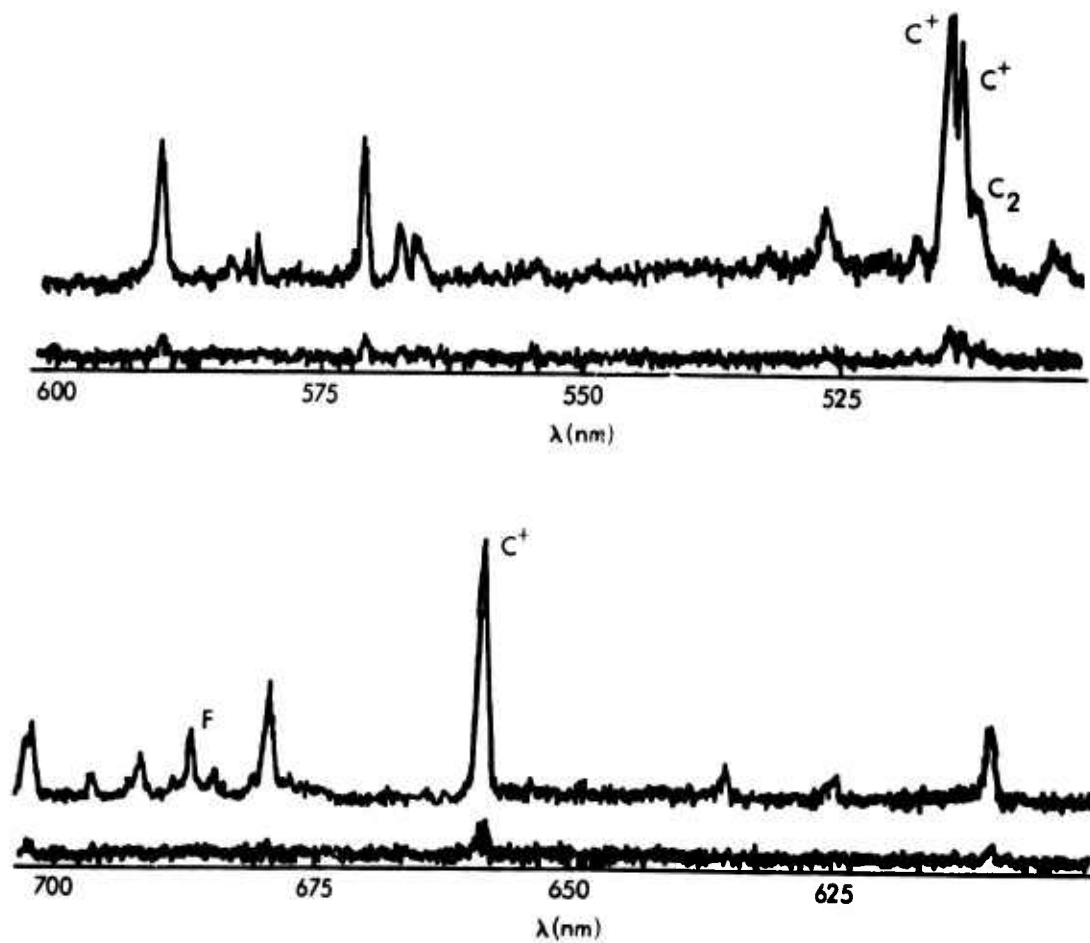
Figure 28b. Pulsed plasma thruster discharge chamber emission spectra and tentative assignments, 500-700 nm.

ignitor plug discharge, viewed normal to the direction of propogation of
the plasma eminating from the plug face, passed directly through a
quartz view window to the quartz focusing lens without the need of a
front surfaced mirror. Figures 29 and 30 show typical line spectra
obtained for the same ignitor plug, S/N3, but different trigger cir-
cuits. Figures 29a and b contain the line spectra from plug S/N3 with
the experimental trigger circuit charged to 1500V for a stored energy of
0.11 joule. For these data, a 1µsec wide gate was used to view the
light coming from the plug during the peak of the plug discharge cur-
rent. Similarly, Figs. 30a and b contain the line spectra from plug
S/N3 with the conventional 3:1 step up trigger circuit charged to an
input voltage of 700V for a stored energy of 0.5 joule. However, for
these data a 20µsec wide gate was in use so that the light from the
ignitor plug was averaged over very nearly the entire duration of the
ignitor plug discharge. Comparison of Figs. 29 and 30 shows that
despite some relative intensity changes, some of which were significant,
there is fairly good agreement between the positions of the more
prominent emission lines.

Analysis of the line spectra shown in Figs. 29 and 30 showed that
many of the emission lines were close to wavelength values tabulated for
known transitions of the various elements comprising the ignitor plug.
However, in all cases the agreement was outside the factory calibrated
wavelength accuracy and resolution of the monochromator. This unexpected
behavior was quite unlike that experienced when viewing the pulsed
plasma thruster arc discharge where good agreement between the experimentally
observed and tabulated wavelengths was obtained. The accuracy of the
monochromator was checked by using a standard mercury arc lamp source

73
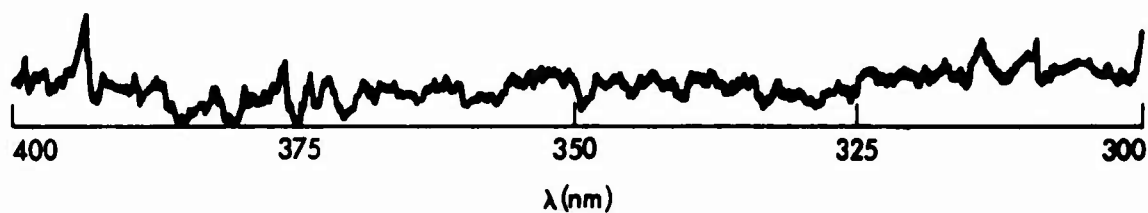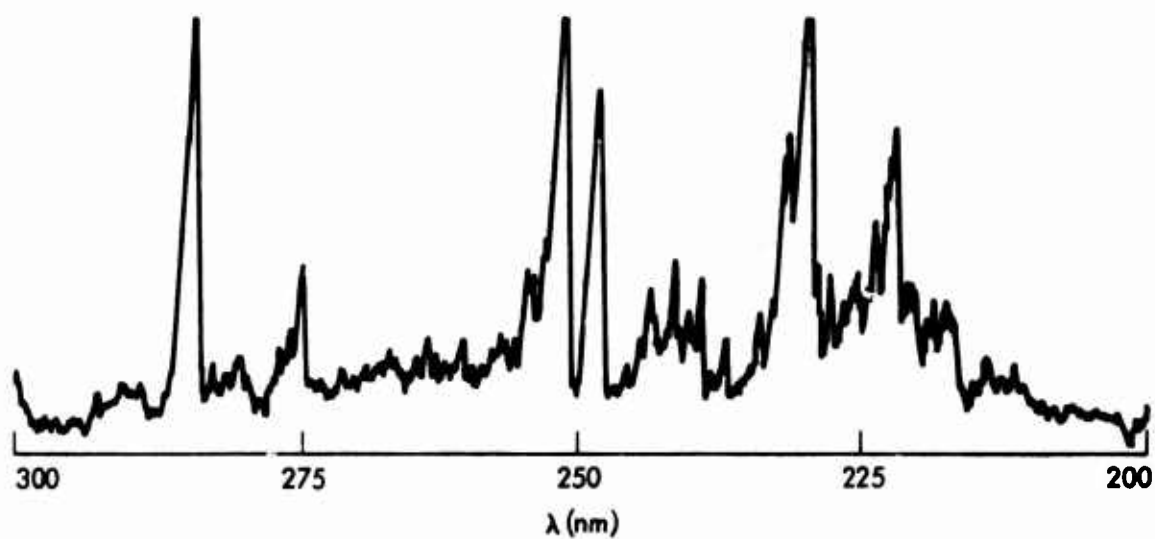
Figure 29a. Plug S/N3 spectra with experimental trigger
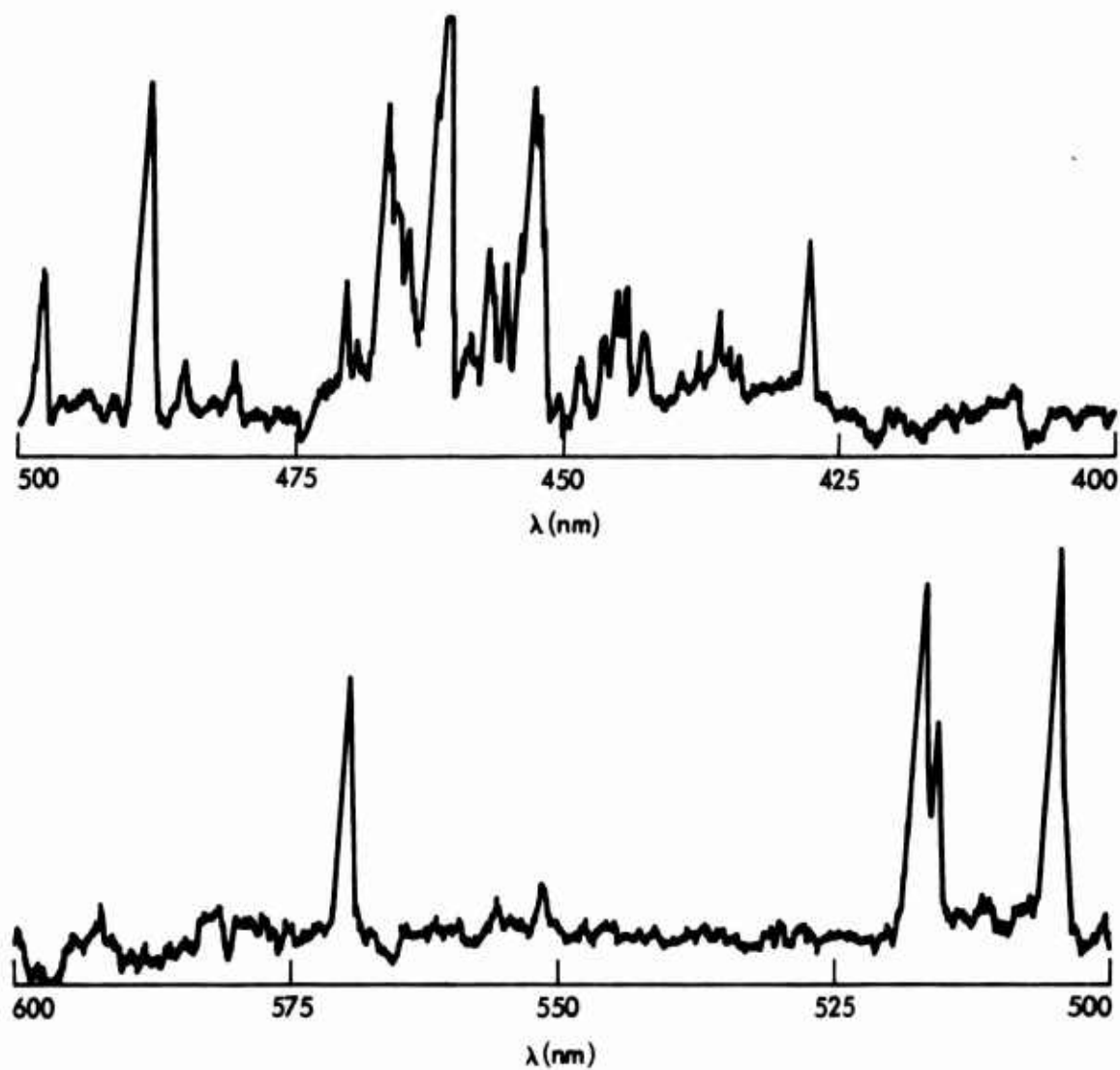circuit, 200-400 nm.

74

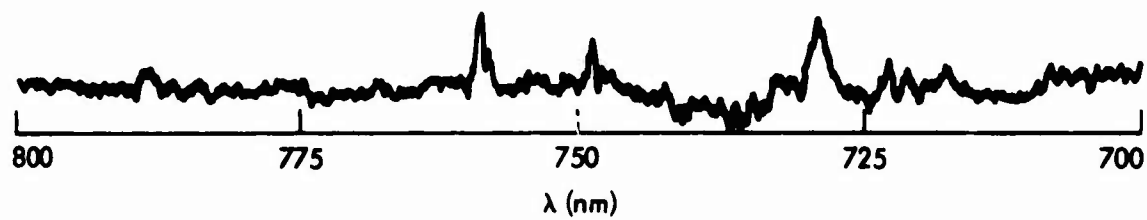Figure 29b. Plug S/N3 spectra with experimental trigger
circuit, 400–600 nm.
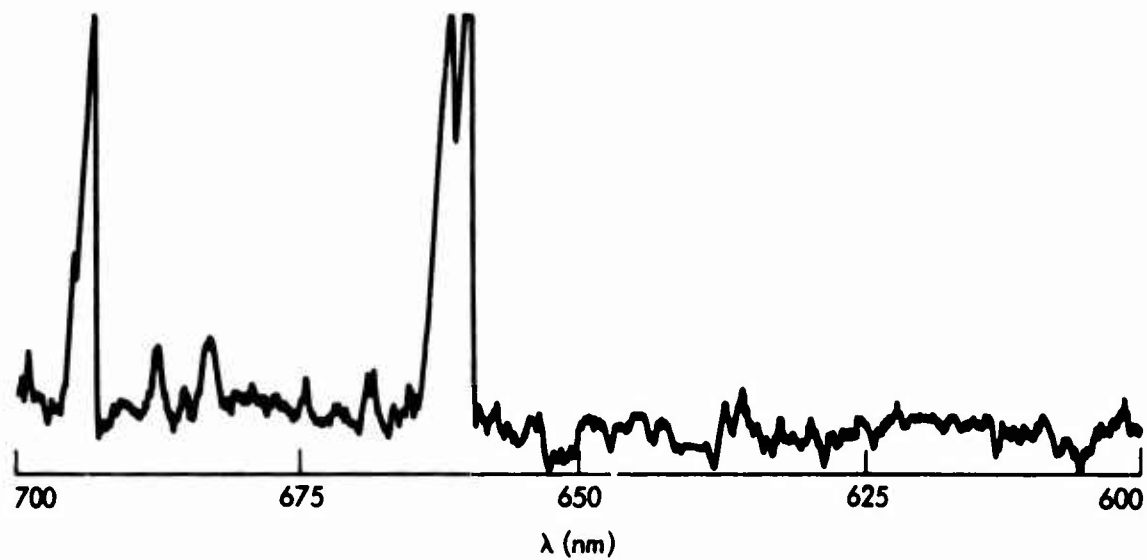
Figure 29c. Plug S/N3 spectra with experimental trigger
circuit, 600-800 nm.
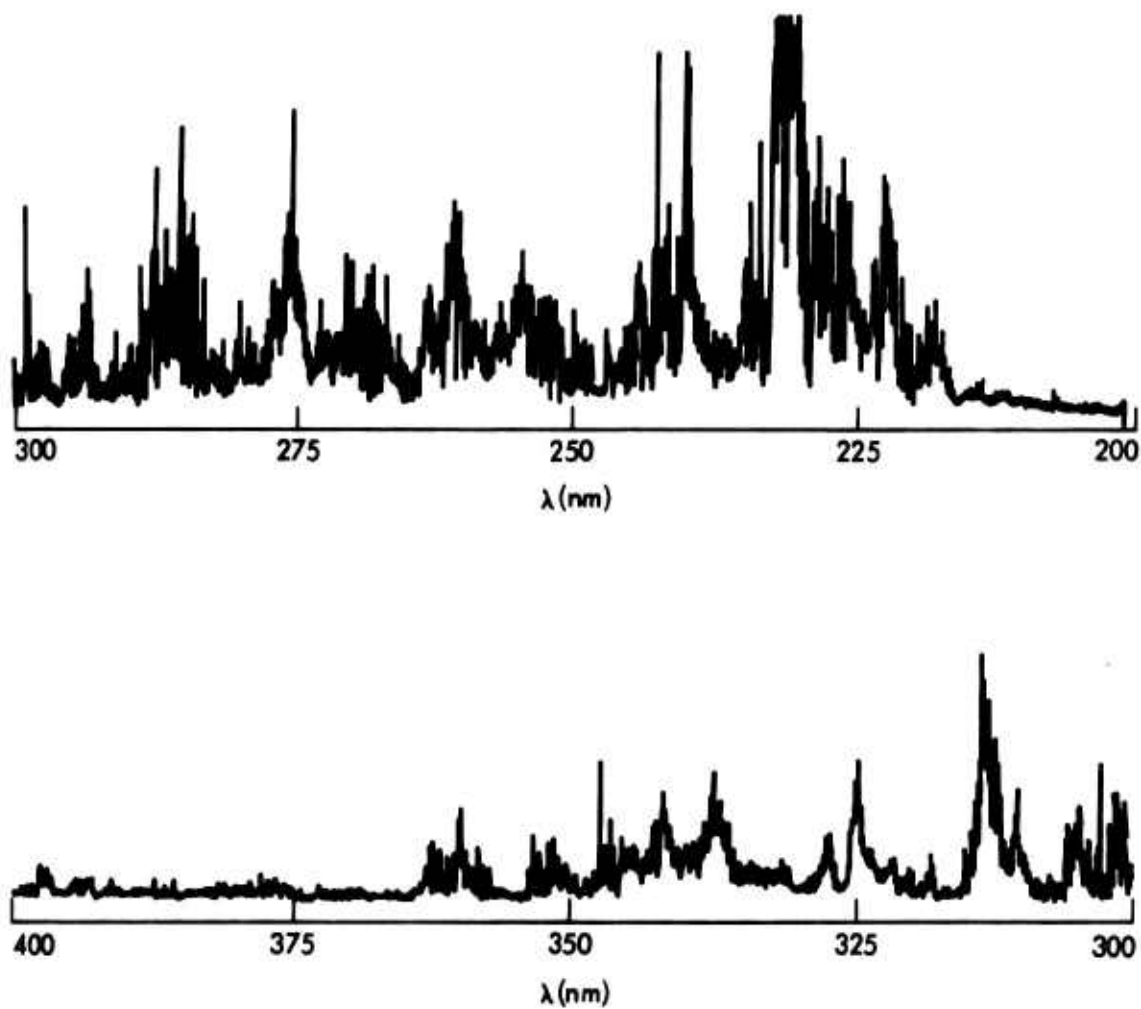
Figure 30a.   Plug S/N3 spectra with 3:1 trigger
circuit, 200-400 nm.

77
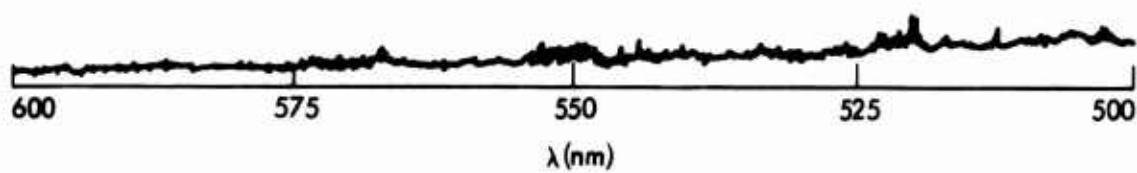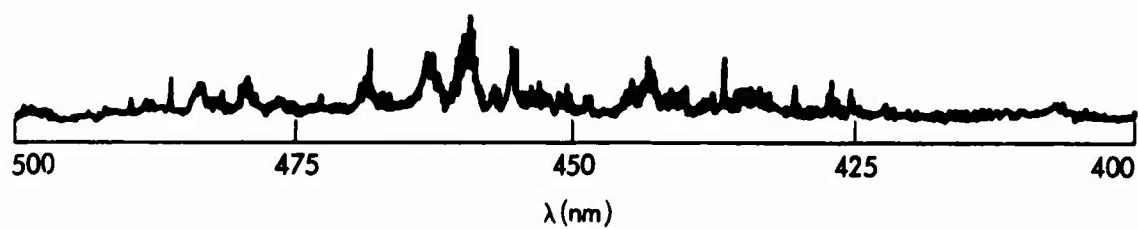
Figure 30b. Plug S/N3 spectra with 3:1 trigger
circuit, 400-600 nm.

and also a standard xenon flashlamp source. In both cases, wavelength
differences were less than the monochromator resolution (±0.25nm).
Calibration checks and tests were also performed on the monochromator
grating drive, the strip chart recorder speed, the effect of the bell
jar residual gas pressure, plus many others to name just a few. No
significant source of error or adverse facility effect was found. It
would appear then that some unknown process was occurring to shift the
emission lines eminating from the ignitor plug plasma. The Stark
effect, pressure broadening and doppler shift effects, were not capable
of producing the wavelength shifts observed during this experiment which
were of the order of a couple of nonometers. It was beyond the scope of
the effort to pursue any further the cause of the wavelength shifts
inherent in Figs. 29 and 30.

4.4 Plug Plume Material Analysis

In order to determine if indeed the ignitor plug plasma plume con-
tained material from the plug anode and cathode electrodes and semi-
conductor ring, an experiment was performed to capture some of this
material. This was done by locating small graphite buttons a short
distance downstream of the plug face. As the plug fired, these buttons
were deposited with material from the plug plasma plume. This deposited
material was analyzed by EDAX (Energy Dispersive Analysis of X-rays)
techniques. Figure 31 shows a material composition spectrum, with
relative abundancies qualitatively indicated by peak height, for a
graphite button located close to the plug axis. It is evident from Fig.
31 that portions of the Kovar plug anode and Inconnel plug cathode are
indeed major constituents of the ignitor plug plasma plume. Similarly,

79
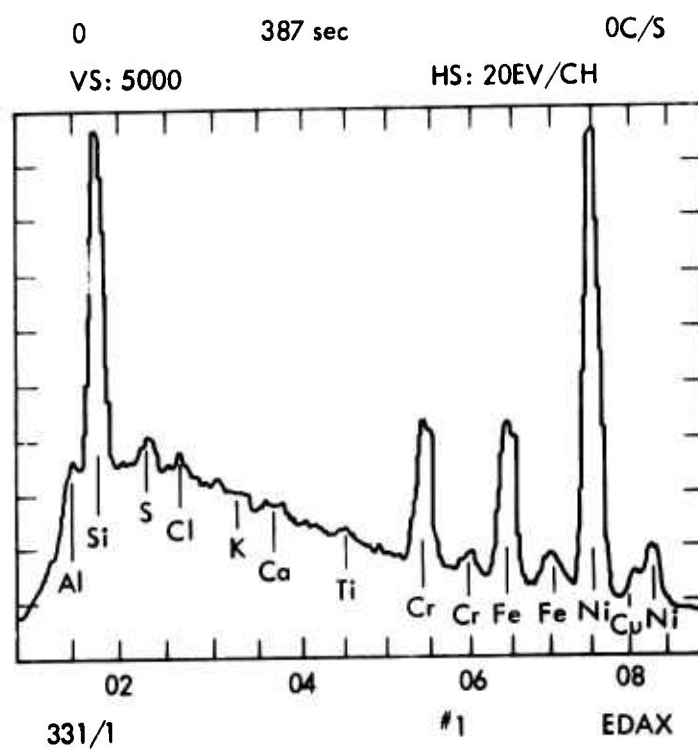
Figure 31.   EDAX analysis of graphite button deposit composition
from plug plasma.

80

the plug semiconductor element, which previous tests have shown com-
prises Cu Cl, K, Ca, Al, and Si, is also present in detectable quanti-
ties. The results of Fig. 31 indicate that relatively strong Si, Fe,
Ni, and Cr spectral lines should be observed in the ignitor plug plasma
plume. The fact that lines very close to various excitation and
ionization levels of these species were observed and that the equipment
appeared to be set up accurately, indicates that some process or
processes are occurring to shift these lines which at present is not
understood.

4.5 Plug Plasma Velocity Measurements

Experimental Apparatus:

Two spark gap probes were used to measure the velocity of the ignitor
plug plasma plume. The distance between the probes was 1.6cm. The
distance from the first probe to the ignitor plug face was 3.8cm. The
spacing between the two 0.5mm dia. tungsten wires making up each probe
was 0.16 cm. Figure 32 shows schematically the probe arrangement and
associated electronics. These velocity tests were done in the small
metal bell jar mentioned previously. All velocity measurements were
taken using ignitor plug S/N3.

In operation, a capacitor network charged to 500V was placed across
each probe. When the plug was fired, the highly conducting plasma plume
leaving the plug face initiated an arc breakdown between each probe wire
pair as this plume front passed the probes. Since the arc impedance
between each probe wire pair was slightly different because of the

81
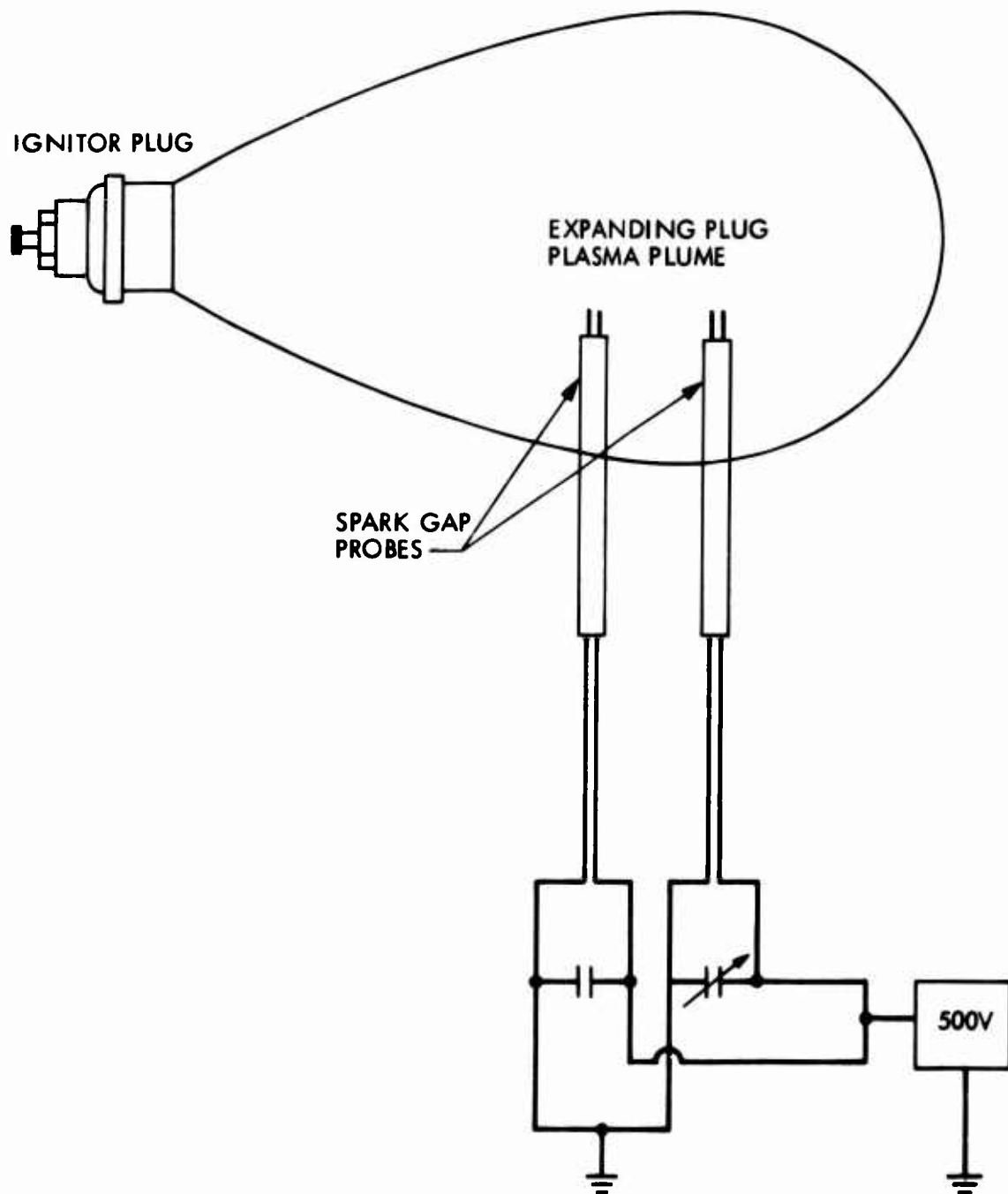
Figure 32. Arrangement of spark gap probes for plug plasma velocity measurements.

expanding nature of the ignitor plug plasma plume, the capacitor network
of the farthest probe was adjusted such that the discharge (or RC) time
constant of each probe was identical. By monitoring the discharging
probe capacitor voltages on a dual beam oscilliscope for a given time
base, equal discharge time constants were ensured by matching the slopes
of the discharging capacitor voltages. The plasma plume velocity was
calculated by measuring the distance in time between these two oscil-
liscope traces and then dividing this into the known probe separation
distance. Figure 33 shows a typical oscilliscope recording of the
discharging capacitor voltages and the construction method used to
determine the plasma plume time of flight.

Plume Velocity Results:

Using the spark gap probes described above, and the 3:4 step up
trigger circuit, various plume velocity measurements were made for
different trigger circuit stored energy values. The trigger circuit
stored energy was varied by changing the energy storage capacitance for
a constant capacitor voltage of 800V. For a trigger circuit energy of
0.64 joule it was possible to get probe traces which had slopes which
could be made fairly parallel. However, as the energy was decreased
it was not possible to get the discharging capacitor voltage slopes
so near parallel. As a result, the subsequent time of flight and velocity
measurements contained increasingly large scatter. Figure 34 shows the
results of these ignitor plug plasma velocity measurements. A plot of
the average of these measurements shows a gross effect of increasing
plume velocity with increasing trigger circuit stored energy. Time and
resources did not allow additional data collection other than that pre-

DUAL BEAM OSCILLOSCOPE TRACE
OF SPARK GAP PROBE DISCHARGES

$\Delta t = 1.05 \mu$ sec
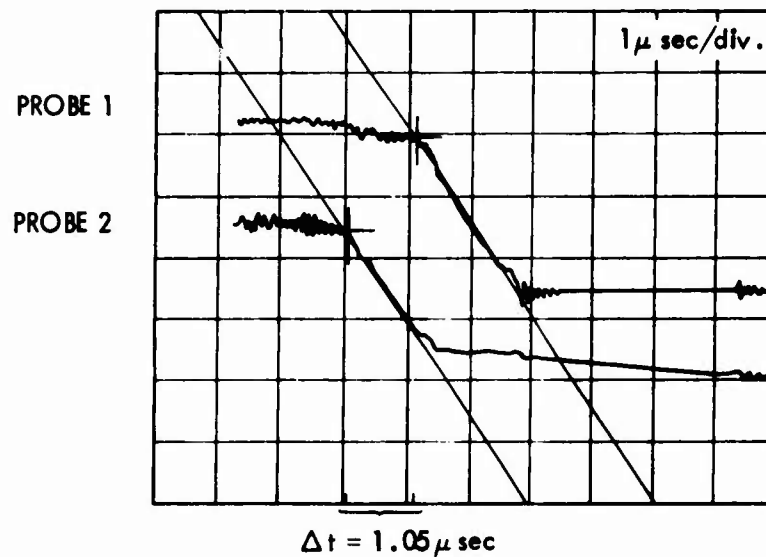
DISTANCE BETWEEN PROBE 1 AND
PROBE 2 WAS 1.59 cm

$\therefore$ PLASMA VELOCITY = 1.59/1.05

PLASMA VELOCITY = 15.1 km/sec

Figure 33. Spark gap probe oscilloscope trace showing method of
time of flight determination.
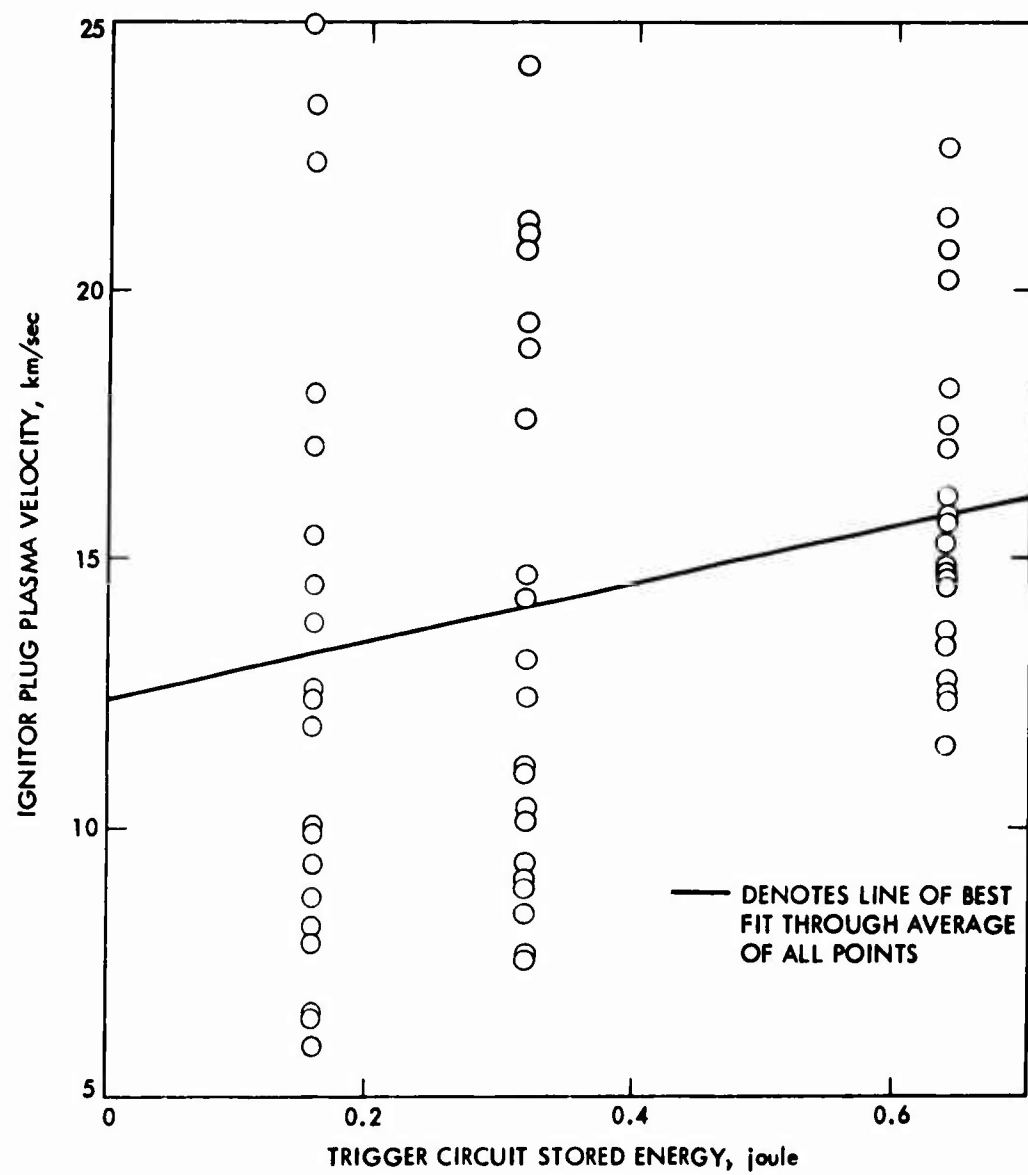
Figure 34. Ignitor plug plasma plume velocity variation for a
constant trigger circuit capacitor voltage.

85

sented in Fig. 34. It is felt that more carefully constructed spark gap
probes of a smaller size would have greatly reduced the data scatter
present in Fig. 34.

From Fig. 34, a typical value for the ignitor plug plasma plume
velocity is about 1.5×10^4 m/sec. Since the separation between the one-
millipound pulsed plasma thruster anode and cathode electrodes is 7.0cm,
it would appear that about five microseconds after the plug fired, the
thruster should fire. This is not the case and current is observed to
start leaving the thruster capacitor bank a few nanoseconds after the
plug has fired. In addition, the 2.4KV potential difference between the
PPT discharge chamber electrodes is more than sufficient to prevent a
typical plug plasma ion initially moving at 1.5×10^4 m/sec from ever
crossing this gap. From these considerations it is not immediately
apparent how the ignitor plug fires the thruster. Section 5 of this
report addresses this dilemma.

4.6 Summary

The results of the ignitor system analysis provided the first experi-
mental data on the dynamic energy and impedance of an ignitor plug
discharge. These data showed that a typical ignitor plug discharge
pulse contained a total energy of only a few tens of millijoule. Also,
the dynamic ignitor plug impedance varied from 0.5 to 0.1 ohm with a
value of 0.2 ohm a reasonable average. Ignitor plug breakdown voltage
was shown to correlate with the rise time of the applied voltage pulse.
Spectroscopic analysis of the plug plasma plume was inconclusive in
identifying major emission lines, however, similar analysis of the PPT

86

arc discharge identified fluorine and carbon in highly ionized states. Analysis of material collected from the plug plasma plume showed that it originated primarily from the plug cathode and semiconductor surfaces. Preliminary plug plasma velocity measurements indicated a typical plume velocity of 1.5×10^4 m/sec.

5.0 IGNITION SYSTEM AND THRUSTER DISCHARGE CHAMBER INTERACTION ANALYSIS

During the course of the PPT ignition study it became apparent that there existed during a single thruster pulse, a complicated exchange of currents between the ignitor plug, coupling element, and thruster energy storage capacitors. This section discusses these interactions and their overall effect on thruster operation.

5.1 Coupling Element Behavior

Figure 35 shows schematically the PPT discharge chamber components and the diagnostic elements as they appeared towards the end of the ignition system study. With these current and voltage probes indicated in Fig. 35 coupled to a fast dual beam oscilliscope, it was possible to monitor the sequence of events occurring during a single thruster pulse. One of the physically more interesting events was the relationship between the coupling current and coupling voltage. Figure 36 shows oscilliscope traces of these variables for a 94µH coupling inductor and a 1.0 ohm coupling resistor. These traces are presented for a time interval that includes only about the first quarter of the thruster discharge current pulse. It can be observed from Fig. 36 that for both inductive and resistive coupling of the ignitor plug cathode to the thruster cathode electrode, a voltage of approximately 2000 volts was impressed across these coupling elements in a time period of about one microsecond. For both types of coupling elements this voltage remained at a constant value for a time interval that was observed to be as long as 4µsec, but normally was only a couple of microseconds in duration. After this random time interval, the thruster discharge was then observed

88
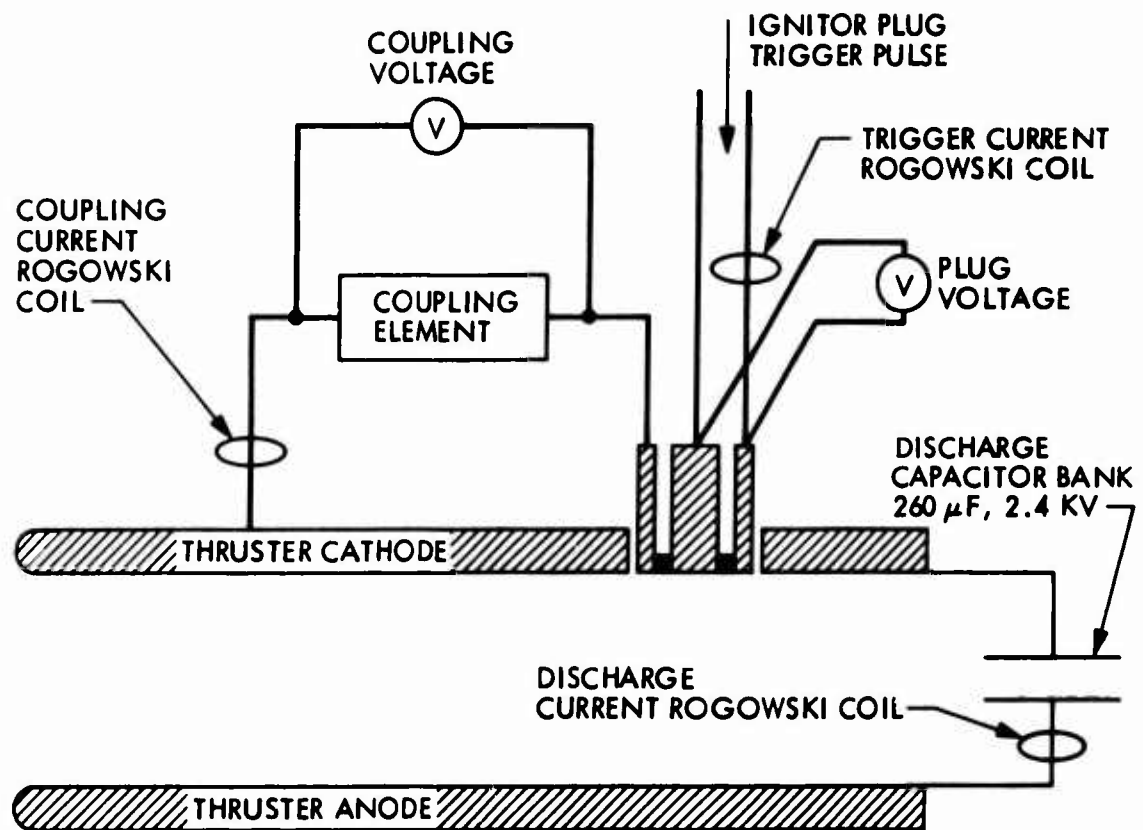
Figure 35. Fully instrumented PPT discharge chamber.

COUPLING CURRENT ↑
57.2 amp/div.

COUPLING VOLTAGE ↑
2000 V/div.

$1 \mu S$

$L_C = 94 \mu H$

COUPLING CURRENT ↑
572 amp/div.

COUPLING VOLTAGE ↑
2000 V/div.

$1 \mu S$

$R_C = 1.0 \Omega$
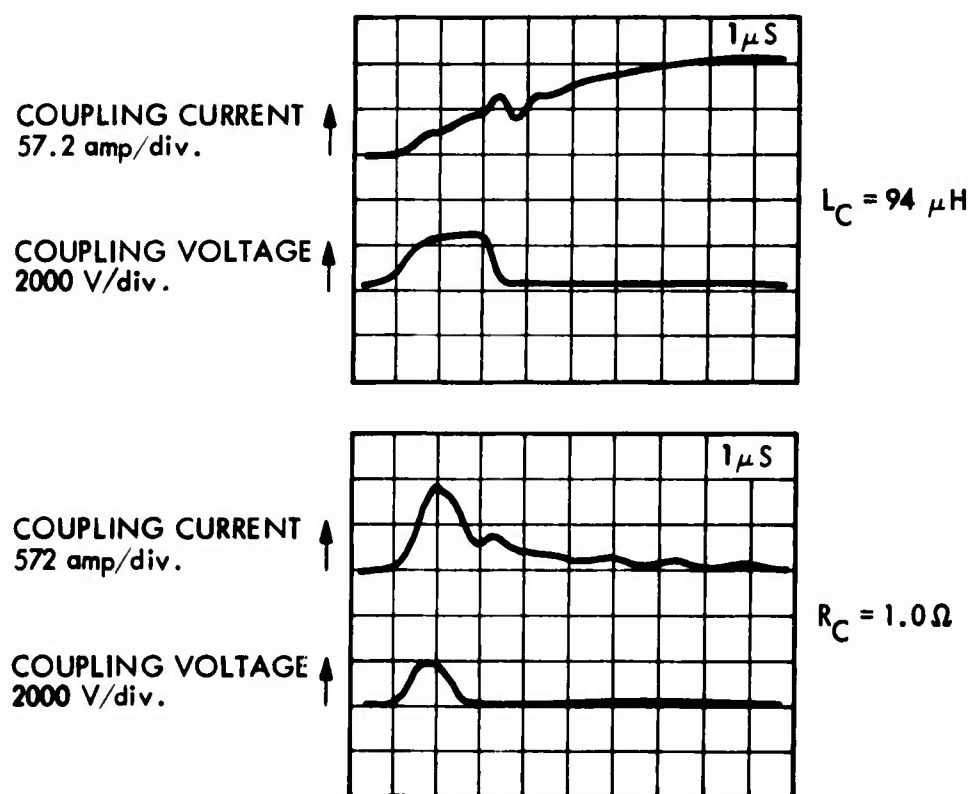
Figure 36. Relationship between coupling current and voltage for
inductive and resistive coupling.

90

to occur and the coupling voltage dropped to a near zero value with either a corresponding drop or continually increasing coupling current. Figure 37 shows a complete sequence of oscilliscope traces for a 300μH coupling inductor which show the relationship of the trigger circuit current, coupling current, coupling voltage, thruster discharge current and the thruster discharge voltage. These data, as also the data in Fig. 36, were obtained using ignitor plug S/N7 and the 1½:1 step down trigger circuit.

5.2 Arc Initiation

Having established the current and voltage behavior of the pulsed plasma thruster discharge chamber circuit elements, one would like to know the rature of the phenomena occurring to produce this observed behavior. Several observations were made which proved crucial in explaining the PPT arc initiation process. From a careful study of many coupling current, trigger current and thruster discharge current oscilliscope traces, it was apparent that a voltage began to be impressed on the coupling element within a few nanoseconds after the ignitor plug arc had begun. Calculations showed that electrons released at the plug when the plug discharge started could cross the gap between the pulsed plasma thruster cathode and anode electrodes in about 5 nsec. It would appear then that almost immediately the plug begins firing some plug plasma electrons, accelerated by the 2400 volt PPT discharge chamber potential, impinge on the thruster anode. However, since the ignitor plug cannot be a source of any net current and since the thruster anode potential is fixed, an ion space charge must develop in the plug plasma. This ion space charge would start to raise the plug plasma and ignitor

91

THRUSTER ARC
CURRENT
50,000 amp/div.

COUPLING VOLTAGE
2000 volts/div.

$L_C = 288 \mu H$

TRIGGER CURRENT
127.7 amp/div.

COUPLING VOLTAGE
2000 volts/div.

$L_C = 288 \mu H$
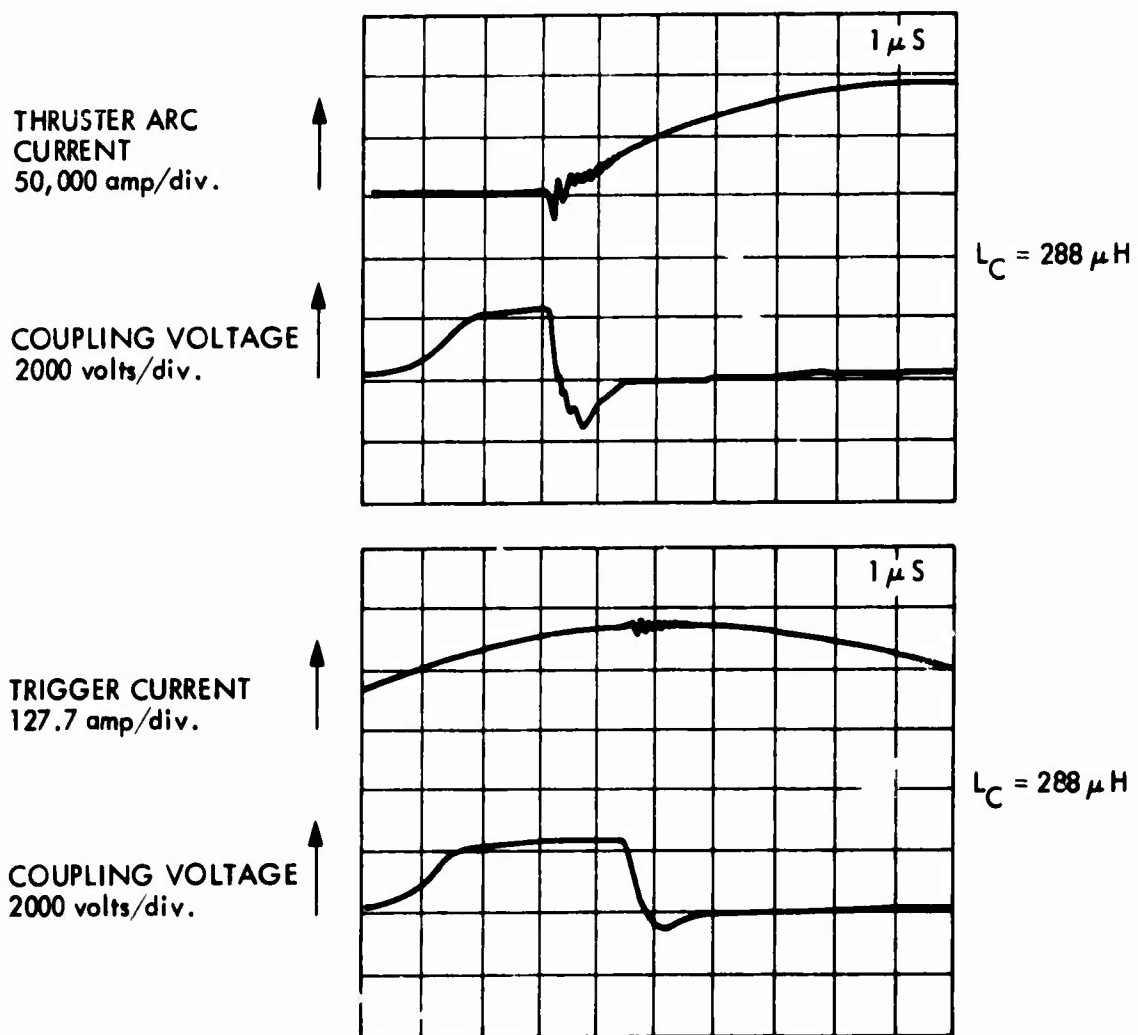
Figure 37a. PPT discharge chamber current
and voltage relationships.

92

COUPLING CURRENT
57 amp/div.

COUPLING VOLTAGE
2000 volts/div.

$L_C = 288 \mu H$

THRUSTER ARC
CURRENT
50,000 amp/div.

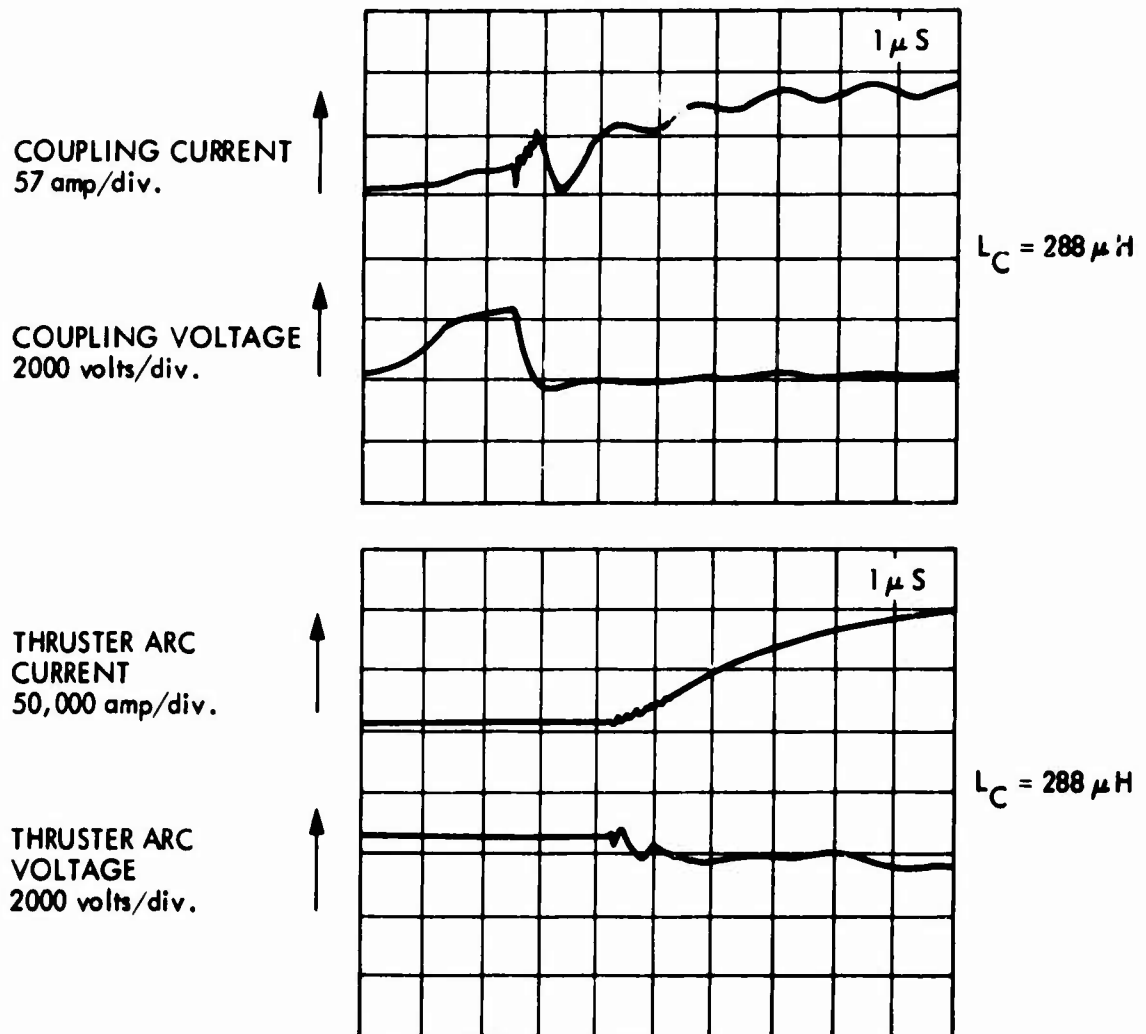THRUSTER ARC
VOLTAGE
2000 volts/div.

$L_C = 288 \mu H$

Figure 37b. PPT discharge chamber current
and voltage relationships.

93

plug positive with respect to the thruster cathode in an effort to
prevent further electron loss. The effect of this elevation in plug
potential would be to allow plug plasma ions to be accelerated to the
nearby thruster cathode electrode to balance the electron current reach-
ing the thruster anode. Up to this point, no net current would be
flowing from the thruster capacitor bank, but a non zero voltage would
be evident on the coupling element. It is speculated that the arrival
of plug plasma electrons at the thruster anode would be sufficient to
initiate an arc discharge between the plug, and thruster anode. Once
this occurred, a sudden rise in coupling voltage to near anode potential
would be expected along with the start of a rising current pulse through
the coupling element. Figure 38 shows this abrupt change in the rising
coupling voltage trace that coincides with the start of the coupling
current pulse. This effect is seen less clearly in Figs. 36 and 37
also.

The above explanation is believed to describe the processes leading
up to the formation of an arc between the ignitor plug and thruster
anode. As would be expected, and as is shown in Fig. 36, the current
flowing through this arc is controlled by the coupling element which
presents the dominant circuit impedance to the thruster capacitor bank.
It is conjectured that a number of things might happen to shunt the arc
from the plug face to the thruster cathode electrode and so initiate
the full thruster discharge. Some possibilties are that this preliminary
arc to the ignitor plug could cause sufficient heating of the nearby
teflon fuel bars to cause significant sublimation to occur. The re-
sultant vapor pressure could then become sufficiently high to create a
Paschen breakdown along the fuel bar faces to start the thruster dis-

94

COUPLING CURRENT
142.5 amp/div.

COUPLING VOLTAGE
500 volts/div.

$5 \mu S$

$L_C = 288 \mu H$

Figure 38. Non zero coupling voltage for zero coupling current.

charge. Also, since a nearly 2.4KV potential difference exists between the plug and surrounding cathode, an arc could occur between these surfaces releasing secondary electrons from the thruster cathode to go to the thruster anode and initiate an arc directly between these electordes. Or finally, and perhaps most plausible, the initial arc between the plug and thruster anode produces an expanding plasma which eventually brings the cathode electrode into conduction with the anode directly. Certainly, whatever the mechanism at work to initiate the main thruster arc, the time interval between the thruster anode to plug arc and the start of the thruster anode to cathode arc is unpredictable, can be a few microseconds long and varies from shot to shot.

5.3 PPT Equivalent Circuit

From the previous discussion it is apparent that there are many current paths that can exist in the PPT discharge chamber. A current path between the plug and thruster cathode was speculated to possibly explain the main arc initiation. While the main arc might not be initiated in the manner described, evidence for this current path was noted. This evidence was arc damage in the form of erosion and localized melting, on the side of the plug cathode, well removed from the plug face. Such damage could have occurred only as a result of an arc to the surrounding thruster cathode electrode. Since the coupling voltage dropped to a near zero value every time the thruster fired, this arc must have always occurred. Similarly, it was observed that there was a definite interaction between the trigger circuit current pulse and the coupling current pulse after the main discharge had been initiated. It was concluded that with conventional long pulse length trigger circuits

96

which continued to fire the plug long after the thruster discharge was
initiated, the main arc plasma formed a current path between the plug
anode and the thruster cathode through the coupling element. The desire
to eliminate this extraneous current path was part of the motivation in
designing the short pulse length trigger circuit described in section
three.

Other current paths were observed and can be conjectured to exist in
the pulsed plasma thruster discharge chamber. Figure 39 summarizes
these current paths by presenting an equivalent circuit which it is
believed is a reasonable first cut representation of the thruster
discharge chamber after the main arc has initiated.

5.4 Summary

The results of the ignition system and thruster discharge chamber
interaction analysis showed that pulsed plasma thruster arc initation is
a complex process that occurs in at least three distinct steps. These
steps have characteristic time constants of a few nanoseconds, a few
hundred nanoseconds and a few micro seconds. Also, it was shown that
nearly the full thruster capacitor voltage is impressed across the
coupling element in slightly less than a microsecond. As a consequence,
this element must be constructed to accomodate this voltage stress
without failure. An equivalent PPT dynamic circuit was devised which
can be used to make qualitative predictions about the types of inter-
actions to be expected between pulsed plasma thruster discharge chamber
components.

WHERE:

L_C = COUPLING INDUCTOR

R_P = PLUG SEMICONDUCTOR RESISTANCE

C_D = DISCHARGE CAPACITOR

L_T = TRIGGER CIRCUIT SECONDARY WINDING

R_C = STRAY COUPLING RESISTANCE

R_{CA} = THRUSTER CATHODE TO ANODE DISCHARGE IMPEDANCE

$R_{A_p C_p}$ = PLUG ANODE TO CATHODE DISCHARGE IMPEDANCE

$R_{C_p A}$ = PLUG CATHODE TO THRUSTER ANODE DISCHARGE IMPEDANCE

$R_{A_p A}$ = PLUG ANODE TO THRUSTER ANODE DISCHARGE IMPEDANCE

$R_{A_p C}$ = PLUG ANODE TO THRUSTER CATHODE DISCHARGE IMPEDANCE

$R_{C_p C}$ = PLUG CATHODE TO THRUSTER CATHODE DISCHARGE IMPEDANCE

Figure 39. Suggested one-millipound PPT equivalent circuit.

6.0 EXTENDED LIFE TEST

As a conclusive means of verifying the results and performance pre-
dictions obtained during the many experiments discussed in the pre-
ceeding sections, an extended life test of the pulsed plasma thruster
was undertaken. This test was performed with ignitor plug S/N6 which
was inductively coupled to the thruster cathode and was operated with
the experimental trigger circuit discribed in section 3. Unfortunately,
numerous problems occurred throughout the extended life test of plug
S/N6. The most serious of these problems was seizure of the teflon fuel
bars approximately 400,000 pulses into the test which seriously preju-
diced subsequent ignitor plug operation. This section discusses the
major life test results.

6.1 Test Conditions

For the duration of the life test of plug S/N6 (approximately three
months), the thruster was operated at a pulse repetition rate of 0.2Hz
and a thruster energy storage capacitor charging voltage of 2400 volts.
Vacuum facility operation was unattended and data on plug operation was
usually collected in the morning of each operating day. As described
previously, several problems occurred throughout the duration of the
life test. These problems necessitated opening the vacuum tank on three
separate occasions. The longest the vacuum tank was open and the
thruster exposed to air was not more than two hours. During those
times the vacuum tank was open, the thruster was not refueled nor were
the fuel bars moved, however, marks were put on the fuel bar holders to
indicate the current fuel bar positions and usage. It was the intended

aim of this experiment to continue the life test until the fuel bars in the pulsed plasma thruster were consumed. This was expected to take about 1.25 million pulses.

Initially, a 1000µH coupling inductor was in use on plug S/N6. Similarly, the initial experimental trigger circuit configuration had a 0.1µF energy storage capacitor which was charged to 3000 volts. An EG&G Model XKN-26 kryton switch tube, which had a higher gas fill pressure than the previously used KN-26 tube, was used in the trigger circuit in order to prolong tube life. Mostly as a result of component failure, several coupling inductor and trigger circuit changes were implemented throughout the duration of the life test. As a consequence of this, when the test was involuntarily terminated, a 180µH coupling inductor with the 1½:1 step down trigger circuit charged to 900 volts were in use. A vacuum facility failure, resulting in a partial loss of vacuum, created an unclearable thruster electrode short which forced the termination of the life test after 1.15 million pulses.

6.2 Life Test Results

Figure 40 shows a plot of the resistance history of ignitor plug S/N6 throughout the extended life test. Also included in Fig. 40 is the variation of total energy in the ignitor plug discharge for the test period. The labelled annotation marks are explained below.

A - Start of test, initial plug resistance of 2200 ohms

B - Plug resistance measuring circuit relay seized

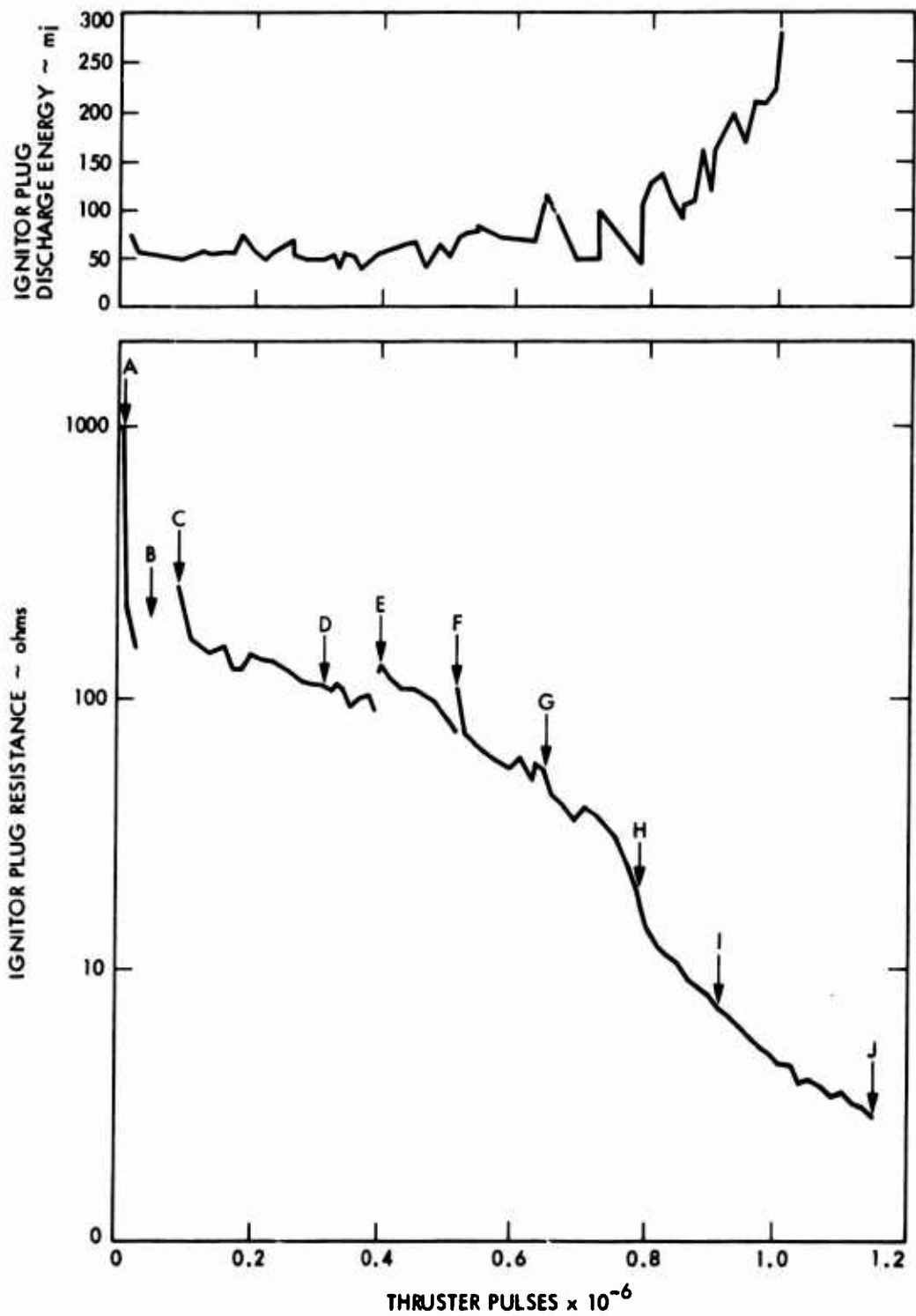C - Tank open. Fused trigger circuit charging resistor replaced.

100

Figure 40. Plug S/N6 extended lifetest results.

101

Trigger circuit placed outside of vacuum tank. Seized relay circuit removed.

D - 288μH inductor remotely switched in to replace 1000μH coupling inductor.

E - Tank open. High voltage short in coupling element stepper switch. Stepper switch box deleted and 288μH inductor hard wired into thruster. Plug surface visually inspected and found to have very slight traces of carbonaceous deposit on plug face. Positon of fuel bars noted.

F - Tank open. 180μH inductor wound with 3KV test wire substituted for 288μH inductor in which it was thought a high voltage short had developed. New kryton installed in trigger circuit and 0.1μF trigger capacitor replaced with 0.25μF unit.

G - Trigger circuit kryton failure. New Kryton installed.

H - Kryton failure. Installed 1½:1 step down trigger circuit operating with 600 volts on input.

I - Increased 1½:1 trigger circuit input voltage to 900 volts.

J - Replaced 1½:1 trigger circuit with initially used experimental trigger circuit operating at 2000 volts and with 0.4μF of energy storage capacitance. Operated thruster for a couple of thousand pulses before a vacuum facility over pressure condition caused a sustained thruster short terminating the life test.

6.3 Comments on Life Test

Inspection of the thruster at the end of the test showed that the fuel bars closest to the thruster capacitor bank had ceased to move after about 400,000 pulses into the test. The remaining fuel bars

appeared to have had their movements partially restricted also. Figure 41 documents the condition of the thruster at the end of the test (the exhaust nozzle, thruster and fuel bar cover plates have been removed). Deeply scalloped patterns on the fuel bar faces are evident from the figure. Also seen is a large amount of carbonaceous deposit all over the thruster, presumably as a result of poor fuel ablation. Deep gouges were apparent in the anode elctrode with fine copper dust all over the thruster. These gouges indicate that many metallic vacuum arcs occurred as a result of the fuel starvation condition.

Assuming that during the first 400,000 thruster pulses the teflon fuel bars were feeding correctly and that the only problem was a short in the coupling element stepper switch, the high plug resistance values shown in Fig. 40 are impressive. Extrapolating the data trend between 100,000 and 400,000 thruster pulses indicates a one ohm plug resistance value would be reached after about 2.75 million thruster pulses. Since it was known that the faulty stepper switch was acting like a low impedance in parallel with the coupling inductor, it is felt that this extrapolation is conservative because of larger than normal coupling currents being present.

For the first half million thruster pulses, the average ignitor plug discharge energy was about 55 mj. This corresponds to only about 12% of the available 450 mj of trigger circuit energy being transferred to the plug. It is felt that the long lead lengths separating the trigger circuit and plug (about 2m) were responsible for this low transfer of energy. It is interesting to note that the experimental trigger circuit always transferred approximately the same percentage of energy to the

103

Figure 41. Condition of thruster after plug S/N6 life test.

104

plug regardless of plug resistance. By contrast, the 1½:1 step down trigger circuit transferred an ever increasing percentage of energy to the plug as plug resistance decreased, indicating a better impedance match to the plug than the experimental trigger circuit.

6.4 Summary

The results of the extended life test, while heavily prejudiced because of component failure and fuel bar seizure, did demonstrate that the coupling inductor and experimental trigger circuit can keep the plug clean and at a high value of resistance. The energy transfer characteristics of the experimental trigger circuit were inferior to the 1½:1 step down trigger circuit indicating a poorer impedance match between this former circuit and the plug. An energy transfer percentage of about 12% was typical for the experimental trigger circuit while an energy transfer percentage as high as 35% was observed with the 1½:1 step down trigger circuit. This low energy transfer and the failing kryton switch tubes in the experimental trigger circuit, suggest that a more concentrated research effort should be undertaken to improve the impedance matching characteristics and switching reliability of this promising circuit. It is anticipated that the dynamic impedance data for an ignitor plug discharge that was presented in section 4.1 could be of use in designing such an improved impedance matched trigger circuit.

7.0 CONCLUSIONS

A study of ignitor plug operation in a one-millipound pulsed plasma thruster has been performed. The major results of this study may be grouped into the following areas.

Resistive Plug Coupling:

Over the four decade range of coupling resistance values tested (0.001Ω to 10.0Ω) the carbonaceous deposit buildup on the ignitor plug face could not be controlled. Moreover, these test results indicated that intensifying arc attachment to the plug face by decreasing coupling resistance to very low values (while still maintaining the vacuum gap between the ignitor plug and surrounding thruster cathode electrode) did not serve to burn off the accumulated deposit. Instead, this arc appeared to play a role in carrying the carbonaceous products to the ignitor plug face.

Inductive Plug Coupling:

Use of a well insulated, low resistance (< 0.5 ohm) coupling inductor of at least 300μsec time constant with an inductance value of between 150-1000μH, resulted in very low accumulations of carbonaceous deposit on the ignitor plug face. This deposit reduction arose from the ability of an inductor to dampen out the large coupling currents that would otherwise result from arc attachment to the ignitor plug face from the thruster discharge.

Plug Trigger Circuit:

A decrease in the amount of plug deposition was also demon-
strated through the use of an experimental trigger circuit which
produced large plug discharge currents and very short pulse
lengths. This high voltage trigger circuit demonstrated reliable
plug firing over at least a three decade plug resistance range
extending down to a couple of ohms.

Plug Erosion:

Ignitor plug erosion was shown to occur simultaneously with the
accumulation of the carbonaceous deposit on the plug face. Most
of this erosion was from an embrittlement phenomenon which could
be related directly to the amount and location of this carbonaceous
deposit and may be caused by chemical attack of the plug base
metals. A lesser amount of erosion occurred from normal plasma
sputter processes and a still lesser amount was caused by plug
vaporization from the trigger circuit plug discharge current
pulse.

Plug Operating Characteristics:

The results of the ignitor system analysis provided the first
experimental data on the dynamic energy and impedance of an
ignitor plug discharge. These data showed that a typical ignitor
plug discharge pulse contained a total energy of only a few tens
of millijoule. Also, the dynamic ignitor plug impedance varied

107

from 0.5 to 0.1 ohm with a value of 0.2 ohm a reasonable average. Ignitor plug breakdown voltage was shown to correlate with the rise time of the applied voltage pulse. Spectroscopic analysis of the plug plasma was inconclusive in identifying major emission lines, however, similar analysis of the PPT arc discharge identified fluorine and carbon in highly ionized states. Analysis of material collected from the plug plasma plume showed that it originated primarily from the plug cathode and semiconductor surfaces. Preliminary plug plasma velocity measurements indicated a typical velocity of 1.5×10^4 m/sec.

Plug and Thruster Discharge Interactions:

The results of the ignition system and thruster discharge chamber interaction analysis showed that pulsed plasma thruster arc initiation is a complex process that occurs in at least three distinct steps. These steps have characteristic time constants of a few nanoseconds, a few hundred nanoseconds and a few micro seconds. Also, it was shown that nearly the full thruster capacitor voltage is impressed across the coupling element in slightly less than a microsecond. As a consequence, this element must be constructed to accomodate this voltage stress without failure. An equivalent PPT dynamic circuit was devised which can be used to make qualitative predictions about the types of interactions to be expected between pulse plasma thruster discharge chamber components.

The results of this study indicate that even with inductive coupling

and the experimental trigger circuit in use, the life of a single ignitor plug will probably not satisfy the one-millipound pulsed plasma thruster design lifetime requirement of 1.4×10^7 pulses. It is recommended that a study be initiated to determine the feasibility of multiple ignitor plug installations in the ignitor plug cathode. Similarly, it is recommended that an improved trigger circuit (i.e., with a higher percentage of energy transfer to the plug), embodying a similar design philosophy as the experimental trigger circuit developed during this study effort, be further investigated.

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